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الجامعة الأردنيـــــة
كلية الدراسات العليا

التاريـــخ: / /

نموذج رقم (١٨)
اقرار والتزام بالمعايير الأخلاقية والأمانة العلمية وقوانين الجامعة الأردنية وأنظمتها وتعليماتها لطلبة الماجستير

أنا الطالب: محمد عبدالرحمن علي أبو سعدان الرقم الجامعي: (٨٠٨٠٧٦٠)
تخصص: ميكانيك الكليـــــة: الهندسة

عنوان الرسالة: Design and characterization of miniaturized Fluid generator for electric power Generation

اعلن بأنني قد التزمت بقوانين الجامعة الأردنية وأنظمتها وتعليماتها وقراراتها السارية المفعول المتعلقة باعداد رسائل الماجستير عندما قمت شخصيا" باعداد رسالتي وذلك بما ينسجم مع الأمانة العلمية وكافة المعايير الأخلاقية المتعارف عليها في كتابة الرسائل العلمية. كما أنني أعلن بأن رسالتي هذه غير منقولة أو مستلة من رسائل أو كتب أو أبحاث أو أي منشورات علمية تم نشرها أو تخزينها في أي وسيلة اعلامية، وتأسيسا" على ما تقدم فانني أتحمل المسؤولية بأنواعها كافة فيما لو تبين غير ذلك بما فيه حق مجلس العمداء في الجامعة الأردنية بالغاء قرار منحي الدرجة العلمية التي حصلت عليها وسحب شهادة التخرج مني بعد صدورها دون أن يكون لي أي حق في التظلم أو الاعتراض أو الطعن بأي صورة كانت في القرار الصادر عن مجلس العمداء بهذا الصدد.

توقيع الطالب: .... التاريخ: ٢٠١١ / ٨ / ١٦

DESIGN AND CHARACTERIZATION OF MINITURIZED FLUID GENERATOR FOR ELECTRIC POWER GENERATION

BY

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Faculty of Graduate Studies

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August 2011

This Thesis/Dissertation (Design and characterization of miniaturized fluid generator for electric power generation) was successfully defended and approved on

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ACKNOWLEDGMENT

During my work, many people helped me to finalize this thesis, firstly; I would like to express my gratitude to my supervisor Dr. **Moudar Zgoul** for his continuous support and guidance. I have gained a lot of experience through working with him, not only in my studies, but also in my personal life. I am also very thankful to my co-supervisor Dr. **Ala'aldeen al-Halhouli** for the valuable discussions and suggestions throughout the work. Through his supervision, I developed my research abilities in power generation systems and measurements. I must not forget to mention my deep appreciation and thanks to my parents and my wife who had and still support me through my education.

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NOMENCLATURE

A: cross-sectional area of the channel.

AC: Alternating current.

AC1: cross-sectional area of the coil.

AFM: Axial flux machines.

B: magnetic field.

CNC: computerized.

CW1 & CW2: tangential velocity of the fluid at the inlet and outlet.

dA: cross-sectional area element in vector form.

DC: Direct current.

DTC: Direct torque control.

EMF: Electromotive force.

I: current.

J: current density.

L: length of the wire.

LED: Laser electrical discharge.

m: mass flow rate (kg/s).

MEMS: miniaturized electromechanical systems.

MFS: mass flow sensor.

Nd-Fe-B: Neodymium-Iron-Boron.

P: pressure at the opening to the turbine cavity.

PM: permanent magnets.

PMMA: permanent magnet machines.

R: radial distance from the center of the turbine to the point of impact.

R: resistance.

r1 & r2: radial distance to the point of impact/release on the turbine blade.

RFM: radial flux machines.

RPM: revelation per minute.

T: tesla

V: voltage.

Greek Symbols

∂E/∂t: displacement current.

∇ x B: curl of the magnetic field.

μ: micro**.**

V_N **:** Velocity in the perpendicular direction.

Θ: angle between the magnetic field and the cross-sectional area.

ρ: wire resistivity.

T: net torque exerted by or acting on the rotor.

Φ: magnetic flux

ω: angular velocity of the rotor.

Ω: ohm

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ABSTRACT

Energy density available from batteries is increasingly becoming a limiting factor in the capabilities of portable electronics. As a result, there is a growing need for compact high energy density sources. This work presents a design, fabrication and testing of a meso-scale permanent magnet generator based on teflon fabrication technology. Experimental investigation was carried out in this work, a number of miniaturized generators were built and experimental setup was developed for generator testing parameter includes number of winding turns per slot of the stator, number of magnets inserted to the rotor and speed has been investigated. The generator was tested experimentally to show that the device can generate milliwatt to watt level power. A 20 mm diameter magnetic rotor is spun above copper windings magnetic flux induces voltage as conforms to Faraday's law of induction. These investigations have demonstrated the feasibility and scalability of magnetic devices for power generating applications. The generator has delivered a 1.45 W to match resistive load of 30 Ω at rotational speed of 6000 rpm.

Chapter 1
Introduction

1.1 Introductions:

As the size and weight of portable devices are increasingly dominated by electromechanical systems, there is a growing demand for smaller, lighter power systems with outputs ranging from microwatts to tens of watts (senesky and Sanders, 2004). Nowadays, electrical generators account for 65% of the worldwide energy consumption. As environmental concern increases, electrical drives with higher efficiency are desirable. Thus, replacing conventional induction machines with Permanent Magnet (PM) synchronous machines have recently gained great interest, particularly as the price of PM materials decreases. Indeed, PM machines have no rotor winding resulting in lower copper losses, and therefore they feature a higher efficiency than induction machines. Electric generators are one of the key elements of mechanical design, used in many applications ranging from toys to propulsion of full-scale vehicles. Few if any simpler ways exist to produce torque and rotary motion; most electric generators have a single moving part. The interest in producing miniaturized mechanical devices opens exciting new opportunities for miniaturized power generation, because of the need for power supply devices with high energy (small-size, low weight, long duration) that can be used in a large field of applications such as; laptops, mobile phones, robots, and as well for military applications. Typical portable consumer electronics suffer from short operation cycles between charges or replacement, and their overall weight consists largely of battery weight. The need to reduce system weight, increase operational lifetimes, and reduce unit cost

has engendered the field of power generation, high-specific-energy miniaturized power systems. The concept behind this new field is to utilize the energy from miniaturized generators meso-devices to generate power (Arnold et.al, 2007). Thus, a miniature generator device with proper system efficiency would compete with top batteries simply from the fact that the fluid/air is easily replaceable. Although higher efficiencies are needed for generator systems to displace batteries, the high efficiencies obtained in large-scale power systems encourage the development of miniaturized power generation devices using air or fluid, with the expectation that devices with competitive efficiencies can be developed. (Gorla and Khan, 2003). Furthermore, there are specific applications were fluid/air power, is desired and were an air based device will have the added advantage of providing this power directly. There is of course the added issue of environmental considerations related to the use of air or fluid since they are friendly to the environment in most cases and that what make such projects be little different from projects that used fuel to harvest energy from such systems. The power-generation devices addressed in the present chapter are those that aim to generate power in the range of a few watts to ten of watts (Handler et.al, 2004). The corresponding air devices are of the order of centimeter in size (meso-scale), and their fabrication techniques are relatively conventional, in some cases with some miniaturized components. The push toward the miniaturization of electro-mechanical devices and the resulting need for meso-power generation (milli-watts to ten of watts) with low-weight, long-life devices have led to the recent development of the field of miniaturized-scale motors. The meso-power generation field is still young, and unexplored in most cases. However,

considering that it is a new frontier of technological development, several meso-scale motors have been developed that appear to operate with good efficiency.

1.2 Research Focus

The aim of the present study is to develop number of miniaturized generators prototypes in meso-scale (centimeter scale) to improve our understanding of the operation and performance of those generators. This would allow optimum miniaturized generator design with reliable and effective operation. A generalized model was proposed to evaluate the effect of several parameters (number of windings, number of magnets, air gap between stator and the rotor). Experimental work will be carried out to test and then develop the best design with the most appropriate power generation and with the highest output power that the system can generate.

1.3 Thesis outline

This work present experimental investigation for the effect of different parameters such as: number of winding turns, number of magnets used, speed on the output power of a meso-scale generator. Following this introduction, chapter two highlight the relevant literature review in miniaturized generators, pumps and motors discussing the recent development in the power generation systems. Chapter three introduces theoretical background in the axial flux permanent magnet machines and the magnets properties used the designed system. Chapter four presents the calculations for the turbine and discusses the electromagnet induction of the designed system. Chapter five describes the experimental setup used to test the generator while

chapter six discusses of the experimental results and draws the conclusion of this research.

1.4 Dissertation objectives

This study aims at investigating the effect of design parameters: number of magnets used, number of winding turns per slot, number of slots of the stator used, and rotational speed. This investigation carried out through experimental designs to be tested, and the results were compared and related to the different parameters. The specific objectives of the present design were the following:

1- Design and manufacture different prototypes to be tested.

2- Investigating the designed prototypes under different parameters and record the results.

3- Optimize a design from the manufactured prototypes with the best output power generated from the system in the range of milliwatt to watt level.

Chapter 2

Literature review

Introduction:

Miniaturized generator concept depends on actuating the designed generator after placing magnets on rotor, and by running the designed rotor over stator windings which in its turn will induce current in the windings of the stator. A number of experimental and theoretical studies have addressed single –phase, three-phase windings, single or double rotors over single stator and with different numbers and types of magnets. This chapter provides an overview of several types of tested miniaturized motors, pumps, and generators for electrical power generation. Many attempts have been carried out to extract an effective method to obtain the best design of miniaturized motors/generators or pumps with the maximum power generation, some of these attempts will be presented in this chapter.

History and Background

This research ponders on axial-flux machines with one rotor – one stator configuration. This particular axial-flux machine configuration has proven to be the most adequate structure for the considered low-speed industrial applications. The possibility to produce a generator via a frequency converter opens new perspectives in the machine designing since the line frequency (50 Hz or 60 Hz) is no more a limiting factor for the selection of the machine pole pair number. Glockner and Naterer (2006) they use a new materials such as soft magnetic composites and high performance permanent magnets, Possible the improvement of the machine construction and thus the improvement of the machine performance characteristics. Fast development of permanent-magnet synchronous machine is related to the

invention of the high-performance Neodymium-Iron-Boron (Nd-Fe-B) permanent magnet material in 1983. Especially low-speed and variable speed industrial applications are recognized to be a potential application area for such permanent-magnet machines. In several industrial applications induction machines with step-down gearboxes are used in order to obtain the desired rotational speed for the driven machinery. Connecting the generator to the device without a gearbox reduces the maintenance costs as well as the space requirements and improves the reliability of the system. The desired high-performance low-speed direct drive can be achieved by using permanent-magnet machines and new control methods such as the direct torque control (DTC) or other high performance vector control methods. Permanent-magnet machines are well suitable for low-speed applications since their performance, e.g. efficiency and power factor, does not depend on the rotation speed to the same extent as it is the case for induction machines. In integrated systems, an important demand is to select the most suitable electrical machine for a particular application. Traditionally, it has been used almost exclusively machines of the radial-flux type. Due to the development of the permanent magnet materials, for some particular applications, using radial-flux machines seem to be no more the most adequate solution. If the machine axial length is limited by the application demands or if it appears to be possible to integrate the rotor directly into the driven machinery, the electrical machine based on the axial flux topology may be a competitive or even a better choice. Compared to radial-flux machines, axial-flux machines have been manufactured and also less used. Therefore, it is obvious that the process of designing and manufacturing axial-flux machines is still developing. For radial-flux machines, the process of manufacturing is well established since it could be optimized through the enormous amount of induction machines that has

been manufactured during the latest century. The radial-flux permanent-magnet motor can be manufactured based on the same process of manufacturing the induction machine since the required machines parts for both machine types are basically the same. The manufacturing of axial-flux machines requires a different type of production equipment, which demands expensive investments as a result of which the unit price remains high if only a small amount of machines is manufactured. Thus, it must be sought for driving forces that provide the motivation and encouragement that increases the use and construction of axial-flux machines. Such driving forces may arise from the difference of the machine performance or material costs, or directly from the geometrical restrictions set by the particular application requirements. Romero, et al. (2009) presented a generator that capable to extract up to 117 μW of power from body motion walks, employing a non-resonant rotational mechanism the planar generator proposed is composed of a rotor having multiple NdFeB permanent magnet pole-pairs with an eccentric proof mass. The stator has a multi-stacked gear shaped planar coil. A change on the magnetic flux induced a voltage in the coil when the rotor moves because of body movement. A $2Cm^3$ prototype was tested on several body locations while walking. A meso-scale prototype was built with a volume of $2Cm^3$ without the casing. The stator was made by stacking layers of a gear-shaped planar coil 25mm diameter. Coil in width dimensions are limited by the photo plotter resolution on the actual prototypes. The prototype was assembled by placing the stacked planar coil in between the two rotors (1mm gap separation) using an alignment fixture. Jewel bearings were used to provide low-friction rotor support. Coil resistance was calculated as 4.4Ω, but measured as 4.9Ω. Only 2-layer and 4-layer coil designs were tested for the generator prototype because of the ease of assembly. Further prototypes with an

increased number of layers or with smaller coil line width (for a higher number of turns per coil) are expected to produce higher induced voltages and therefore larger power outputs. Larger output voltages are also an advantage for using solid-state diode rectification. Generated energy can be stored in super capacitors or rechargeable batteries for posterior use when there is no body motion activity. Krahenbuhl, et al. (2009) developed a miniature compressed air to electrical power system was carried out, based on radial turbine with electric power output of 150 W. Measurement of the compressed air to electrical power system with maximum revealed electrical power output of 170 Watt, a maximum torque of 5.2 mNm and a turbine efficiency of 52%. The compressed-air-to-electric-power system investigated had a power output of 150 Watt. It is based on the reversal of an existing turbo compressor system, which reaches a maximal pressure ratio of 1:6 at a maximal power input of 150 Watt. The increasing need for high energy density from portable power devices, has led to intense research and development efforts on miniaturized systems with power outputs up to 100 W. Zwyssig and Kolar (2006) In a separate research work a permanent-magnet machine was chosen with the aim of a low system volume, since permanent-magnet flux density remains constant for decreasing machine volume. High-speed operation requires a simple and robust rotor geometry and construction, and excessive mechanical stresses can be limited with a small rotor diameter. Therefore, a radial-flux machine is chosen with a cylindrical permanent magnet encased in a retaining sleeve. A $\mathrm{sm_2co_{17}}$based magnet is chosen because of its outstanding thermal characteristics operating temperatures up to 350 $\mathrm{C^0}$. A slot-less winding is chosen in order to keep the rotor losses low and the stator core manufacturing simple. This leads to a phase current of

3 A for the desired power level and a standard three-phase windings shown in Figure 2.1.

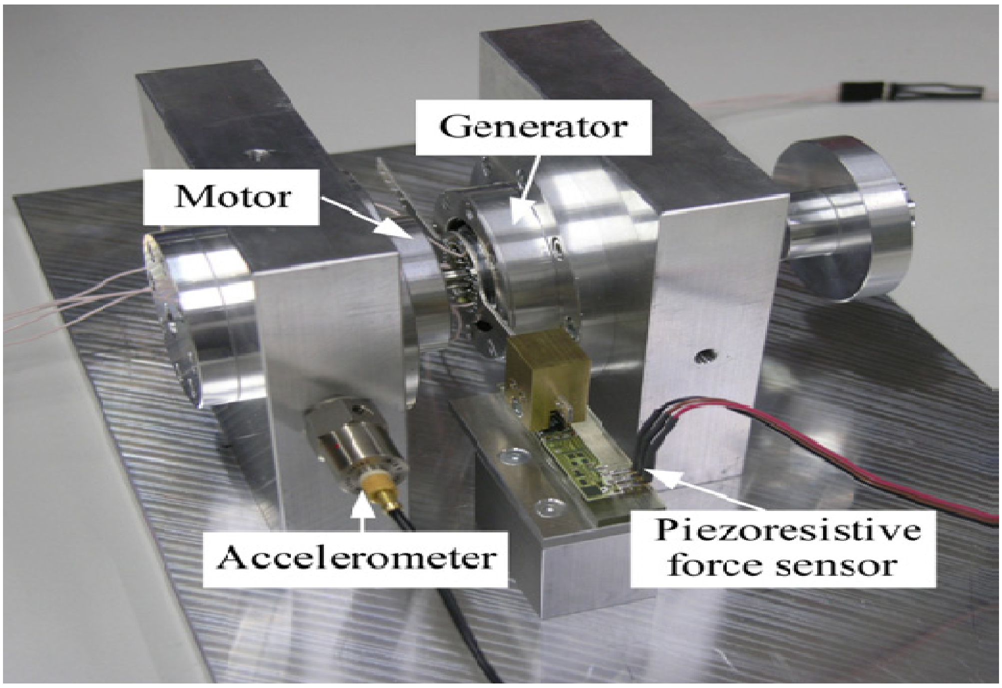

Figure 2.1: photograph of the test bench showing motor, generator and sensors.

(Zwyssig and Kolar, 2006)

To minimize the stator core losses, different magnetic materials are compared and it is shown that amorphous and nano-crystalline materials are the best choices. The rotor is designed with a sufficient safety margin for the mechanical stresses. Titanium is used as a retaining sleeve material in order to limit the stresses on the high-energy sm_2co_{17} magnets. To verify the analytical calculations a test bench has been built, which consists of two machines one is acting as motor and the other as generator on a common shaft. The measurements on the test bench of the back EMF and the torque match the values obtained by finite element simulations. Herrault and Bernard (2010) designed a silicon packaging favors fine control on shape and dimensions in batch fabrication and provides a path toward high rotational speeds, a requirement for ultimate compactness of micro

generators Successful silicon packaging of these micro generators consisted of a winding scheme allowing both nonplanar fabrication and through-wafer interconnects, Laminations built into the silicon for enhanced electrical performance, a balancing scheme for heavy PM rotor, to ensure its maximum performance. The devices were fabricated using bonded silicon wafers, integrated magnetics, and a PM rotor was evaluated at high rotational speeds using an external spindle drive. The generators were electrically characterized, and an output power in excess of 1 W across a resistive load of 0.32 Ω was measured at a maximum speed. A 225% power increase was also experimentally determined due to the addition of a laminated stator back iron. Pan, et al. (2006) applied successfully to micro-apparatus, the study focuses on the design and manufacturing required to obtain a high power generation output, and an analytical model is developed to predict the power output for different designs of micro generators. The theoretical model of this power micro generator is evaluated and compared with experimental results, and it is found that the analytical simulation shows a good agreement with the experimental results. The induced electromotive force (EMF) is 111.2 mV and a maximum power output of 0.412 mW at a frequency of 149.3 Hz is obtained. The experimental results reveal that this micro generator, with eight-pole magnets and four-layer Cu planar micro coils, generates a voltage of 111 mV and has a maximum power output of 0.4 mW at 149 Hz.

Chapter 3
Theoretical background

3.1. Overview

This chapter is to reviews the history and background of the related designs. It will also review the basic operating principles behind a mechanically driven electromagnetic generator.

3.2 Turbine Rotation

The Euler turbine equation (Eq.3.7) is based on the concepts of conservation of energy and conservation of angular momentum (Spakovszky and Waitz, 2007). It is most commonly used to calculate the energy transfer between a fluid flow and a turbine, but can also be used to calculate the energy transfer from a mechanical device such as a compressor or pump, to the fluid flow (Gorla and Khan, 2003)

In linear motion we have seen that work done can be related by the simple equation:

Work done = Force × distance moved in the direction of a force

$$W = Fs \qquad (3.1)$$

We can use the same idea to work out the work done in a rotating system:

Work done = torque × angle rotated

$$W = T\,\theta \qquad (3.2)$$

In linear motion we also found a useful relationship between force and power:

Power = force x speed. (3.3)

We can derive a similar expression for rotational motion:

Work done = energy used.
Power = energy used ÷ time interval
Power = (torque x angle rotated) ÷ time interval

$$P = \frac{T\Delta\theta}{\Delta t} \tag{3.4}$$

But:

$$\omega = \frac{\Delta\theta}{\Delta t} \tag{3.5}$$

Power = torque x angular velocity

$$P = T\omega \tag{3.6}$$

The rate of energy conversion per unit mass is given as

$$p = T\omega = m\omega\,(cw_1\, r_1 - cw_2\, r_2) \tag{3.7}$$

Where

T = net torque exerted by or acting on the rotor

ω = angular velocity of the rotor

m = mass flow rate (kg/s)

cw_1 & cw_2 = tangential velocity, in the direction normal to the radius, of the fluid at the inlet and outlet

r_1 & r_2 = radial distance to the point of impact/release on the turbine blade.

The standard thermodynamic sign convention for the Euler equation is that work done by a fluid is positive, and work done on the fluid is negative. For the scope of this project, the work produced by the turbine will be positive. By extension of the Euler equation, the torque on the rotor can be determined by excluding the angular velocity.

This leaves the equation as

$$T = m\,(cw_1\ r_1 - cw_2\ r_2) \tag{3.8}$$

For this design, Equations 3.7 and 3.8 will be modified accordingly to account for differences in the design and the known variables for the ideal case. For instance, the tangential velocity of the fluid at the outlet is unknown and cannot be accurately measured due to current technological restrictions. The torque, therefore, can only be calculated for the ideal case where the tangential velocity of the fluid at the outlet is zero. Energy loss due to friction between the turbine and its housing is also assumed to be negligible because the turbine is suspended within the fluid. Given these assumptions, the torque acting on the turbine can be simplified to perpendicular force acting on an object at a given distance from the objects center. Torque can therefore be calculated using the previously calculated fluid pressure at the opening to the turbine cavity using the relationship

$$\tau = P\ A\ r \tag{3.9}$$

Where P is the pressure at the opening, A is the cross-sectional area of the channel and r is the radial distance from the center of the turbine to the point of impact on the blade, as shown in Figure 3.1.

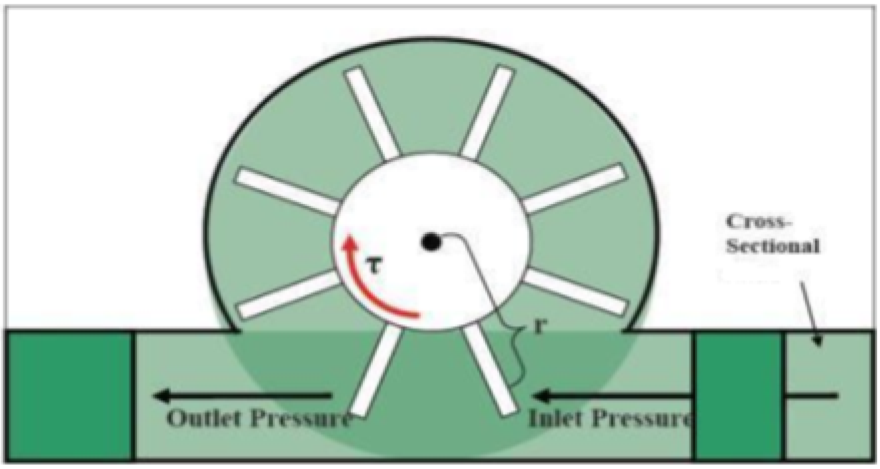

Figure 3.1: cross sectional area view of turbine inlet and outlet pressure.

To calculate the angular velocity of the turbine, the simplified model of a particle in a two-dimensional plane shown in Figure 3.2 can be used because the movement of the turbine is restricted in the z-direction. The turbines movement is also restricted in the radial direction (V_n), so that the velocity is purely in the perpendicular direction (V_t). The turbine's angular velocity is given by

$$\omega = V_n / r \qquad (3.10)$$

The calculations for the ideal angular velocity of the turbine, assuming no loss due to friction or backpressure, should be 628 radians/second. This translates to a rotation rate of approximately 6000 revolutions/minute. Since the turbine and stator are connected via the turbine shaft, the stator should also be rotating at 6000 rpm.

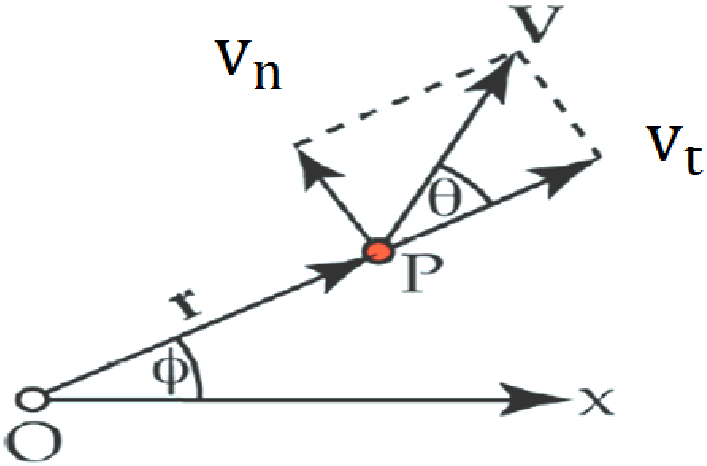

Figure 3.2: Vector diagram for the angular velocity of a particle in a 2-dimensional plane (Angular Velocity**,** 2007**)**.

From Equation 3.7, the rate of energy transfer from the fluid to the turbine can be determined by multiplying the angular velocity of the turbine by the applied torque. Although this is a key figure of merit for turbine designs, it will have limited effect on the overall power output of the device. Rather, it is the electromagnetic portion of the device that will affect the majority of the power output characteristics.

3.3 Electromagnetic Induction

The four fundamental equations of electromagnetism, known as Maxwell's equations, describe the behavior of electric and magnetic fields. Maxwell's 3.11 and 3.12 equations,

$$\nabla \times E = -\partial B/\partial t \quad (3.11)$$

$$\nabla \times B = \mu_0 J + \mu_0\, \varepsilon_0 \partial E/\partial t \quad (3.12)$$

Describe the interaction of electric and magnetic fields and are the most relevant to this project. Equation 3.12, known as Ampere-Maxwell Law, describes the current density (J) and the displacement current ($\partial E/\partial t$) produced by the curl of the magnetic field ($\nabla \times B$). This means that a time changing magnetic field will induce a current in a wire or loop within the field, as illustrated in Figure 3.3 (Flipsen, et al., 2004).

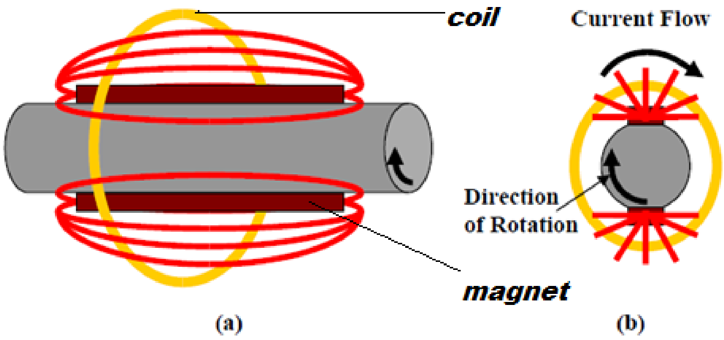

Figure 3.3: Side view (a) and end view (b) illustration of Ampere-Maxwell current induction in a loop of wire (gold) due to a time-changing magnetic field (red).

This method of power generation is the basis for most of today's energy production. All modern power plants, with the exception of solar plants, either superheat a liquid or use the force of gravity acting on water to turn a turbine, which in turn, turns an array of large permanent magnets. These arrays induce a current flow in thousands of coils of wire surrounding them, thus producing the electricity that touches every aspect of human life today. The Ampere-Maxwell Law is also the basic equation that describes the current produced by such devices. Once magnetized, the coil windings on the stator will produce a constant

magnetic field. Once the turbine and rotor begin to move, the coil below the rotor will no longer be sitting in a constant magnetic field, but will instead be immersed in a time-changing magnetic field. As magnet of the rotor passes over a point on the coil, the coil will experience a relatively strong magnetic field due to an increased number of magnetic flux lines penetrating its surface. If the cross-sectional area and either the magnetic field (B) strength or the magnetic flux (Φ) is known, the remaining variable can be calculated using

$$\Phi B = \int B \cdot dA \qquad (3.13)$$

Where dA is the cross-sectional area element in vector form. Equation 3.13 can be simplified to

$$\Phi B = B\ A\ \mathrm{Cos}\ \theta \qquad (3.14)$$

Where $\boldsymbol{\theta}$ is the angle between the magnetic field and the cross-sectional area? This is maximized when $\boldsymbol{\theta}$ = 0º (the field is perpendicular to the area, Figure 3.4a) and minimized when $\boldsymbol{\theta}$ = 90º (the field is parallel to the area, Figure 3.4b). Given this magnetic field strength, the theoretical current can then be calculated using a simplified version of Equation 3.12.

$$\nabla \times B = \mu_0 J \qquad (3.15)$$

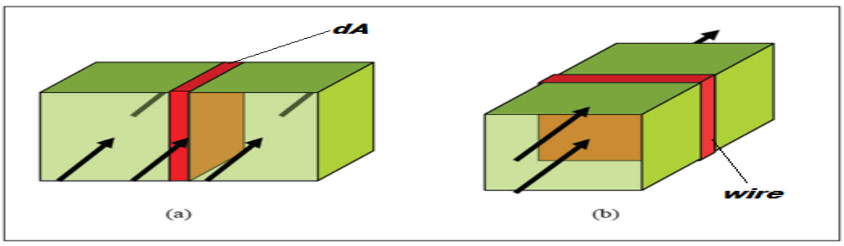

Figure 3.4: Magnetic field lines shown perpendicular (a) and parallel (b) to the cross sectional area of the wire. (Camacho and Olivia, 2006).

Current flowing through the coil will generate a voltage difference between the ends of the coil due to the resistance of the coil material. Equation 3.16 shows that the resistance in a wire is due to the resistivity (ρ) of the material and the dimensions of the wire, where L is the length of the wire and A is the cross-sectional area of the wire (Camacho and Olivia, 2006).

$$R = \rho L/A \quad (3.16)$$

Equation 3.15 assumes that the displacement current component (∂E/∂t) from Equation 3.12 is negligible compared to the current density (J). While this is not strictly accurate, it is sufficient for these rough calculations. Copper has a resistivity of 1.54 x 10^{-8} Ω-m. The coil will have a length is known and for a cross-sectional area of 7.5x 10^{-3} m^2. This will give the coil a resistance value of 7 Ω. using this resistance value, Equations 3.17 and 3.18 give a maximum voltage and an output power in (W).

$$V = IR \quad (3.17)$$

$$P = VI \quad (3.18)$$

The number of the rotor magnets and the coil can be adjusted, however, to increase the power output from the same design, the initial design has the rotor magnets (2, 4, 6, 8). The number of the magnet can be changed during testing by increasing the number of magnets on the rotor and the number of the coil turns in the design. The voltage generated in the coil and the total power output can also be changed by altering the dimensions of the coil. Equation 3.19 shows the voltage generated by current flowing through the coil and Equation 3.20 shows

the output power of the device, both as functions of the cross-sectional area of the coil (Ac_1). The length of the coil was measured through the center of the coil

$$VC = (I \rho L) / Ac_1 \tag{3.19}$$

$$P = (I_2 \rho L) / Ac_1 \tag{3.20}$$

The output voltage curve for the coil cross-sectional area between 2.5 x 10^{-3} $m^2$and 10 x 10^{-3} m^2. The voltage increases as the cross-sectional area of the coil decreases for a maximum value of 3V when the cross-sectional area is 7.5 x 10^{-3} m^2. If both the height and width of the rotor magnets are changed simultaneously, the output voltage curve becomes parabolic

3.4 Chapter Summary

Represent the possibilities inherent in this design. Small changes in any of the four sections of the device have great effects on the overall output power of the device. Also, total power output may be increased by connecting two or more of the devices in series or parallel, depending on the need for either increased current or voltage. One possible problem that these calculations do not illustrate is the danger of overloading the coil. While the voltage and therefore the power is maximized as the cross-sectional area of the coil decreases, trying to push too many electrons, too quickly through that small of a wire may cause the wire to melt or deform. Keeping the coil several times wider than the height of the coil may help to alleviate this possibility by providing increased contact area to the substrate, which acts as an infinite heat sink.

Chapter 4
Testing facility and measurements

4.1Testing facility

In any measurement work, there should be some guidelines that shape the testing for the purpose of having acceptable results, some of these guidelines describe the theory behind measurements which have been discussed in earlier chapters, other guidelines describe the type and range of the devices that need to be used in order to obtain the results. The design objective for this generator is to harvest as much as possible power while having the smallest possible size. The main benefits from the manufactured design are the machine is compact, has lightweight with a short axial length and good ventilation and cooling of the stator windings. The axial-flux PM (AFPM) machine is another possible solution for low speed applications. As suggested by its name in Figure 4.1, the flux from the PMs Flows axially while the current flows in the radial direction Different kinds of AFPM exist, but for low-speed applications, the most commonly studied topology is the Torus machine (Cirani, 2002). Therein, the stator is placed under the rotor that is rigidly connected to the mechanical shaft. The permanent magnets are placed opposite to each other on the two rotor and the stator windings are toroidal (Hakala, 2000).

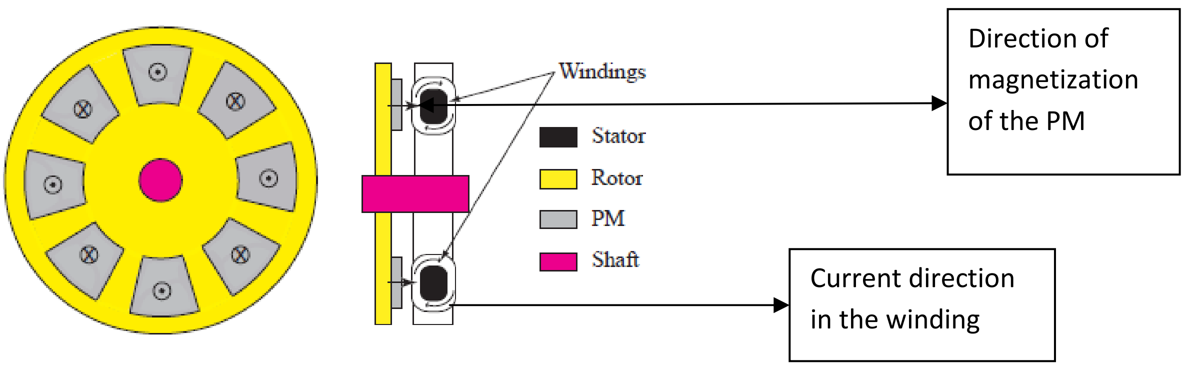

Figure 4.1: axial flux machine with current flows

Figure 4.2 and 4.3 shows the block diagram for testing facility which was used in the present work.

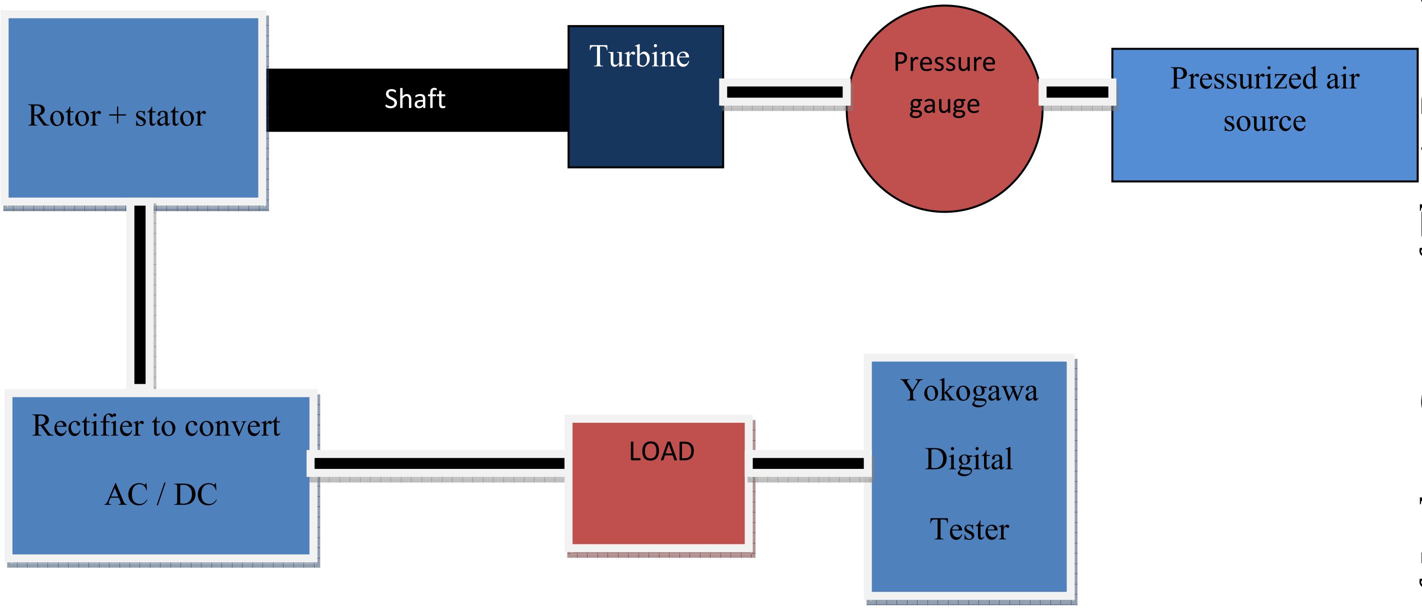

Figure 4.2: block diagram for testing facility

Figure 4.3: Testing facility.

The testing facility consists of a pressurized air source, turbine, generator (rotor, stator), rectifier, load (resistance), and Digital tester.

4.2 Air source:

The pressurized air source used in this work is produced by a compressor which can generate air up to 8 bars as it shown in the Figure 4.4 and it's a fixed /floor mounted piston type air compressor which operates at AC three phase power supply.

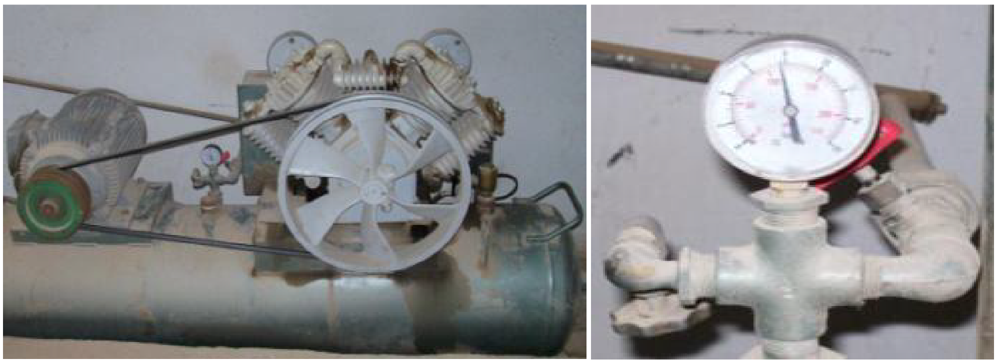

Figure 4.4: Pressurized air gage.

4.3-Manufacturing the rotor and shaft

For the scope of this project we manufactured two rotors with different diameters to study the effect of decreasing the rotor size on the system. The first rotor was of 40- mm in diameter and the second rotor was of 20-mm in diameter and that for the outer dimension of the rotor, but for the inner diameter where the shaft will be placed is about 10-mm in diameter. These two rotors were manufactured from Teflon because of its light weight as well as its high machinability without any complexities. The manufacturing process for this type of rotors it can be accomplished easily with the conventional lathe machines and CNC machines. In designing the rotor we should consider the place where we intend to place the

magnets on the rotor. Thus we have the ability to study their effect from the generated open circuit output voltages. So as shown in Figure 4.5.

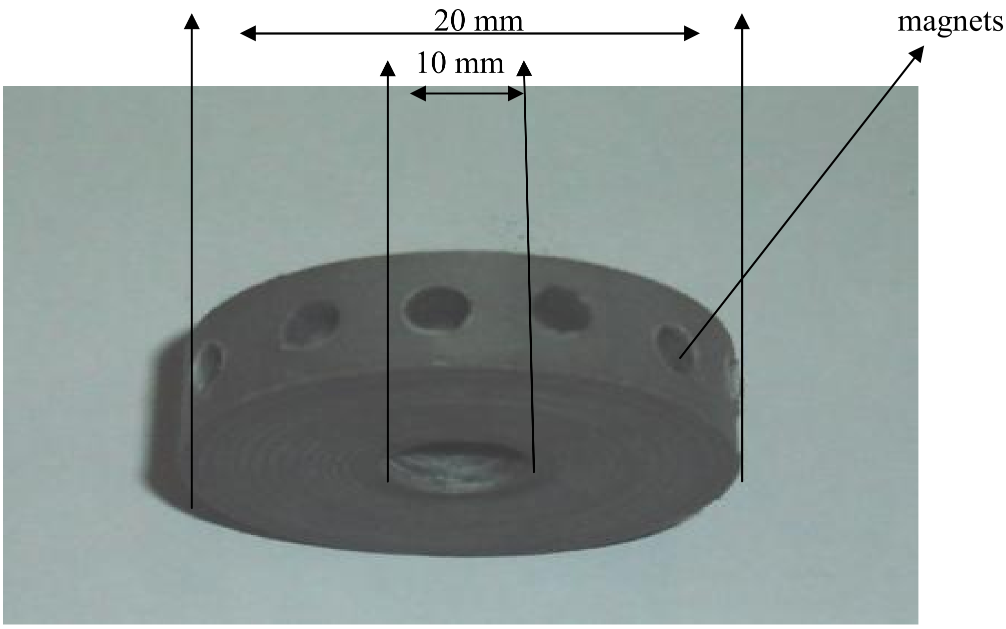

Figure 4.5: Magnets placed to the side of the rotor

The magnets placed to the side of the rotor. As a second design we manufactured another rotor with magnets to be placed at its surface as shown in Figure 4.6. So through experiment will decide which of these two designs have a major effect on the results. And for shaft (10 mm) diameter manufacturing that was one of the easy processes that can be accomplished. The important factor that to be in consideration while manufacturing the shaft is that it has to fit in the rotor with the minimum clearance so the rotor will rotate with the shaft as a one unit. There is an important factor that should be in our account when manufacturing the rotor, which is the imbalance of the rotor which can be defined as the distance between the geometrical center and the center of mass to operate at its maximum performance, the rotor imbalance must be as low as possible.

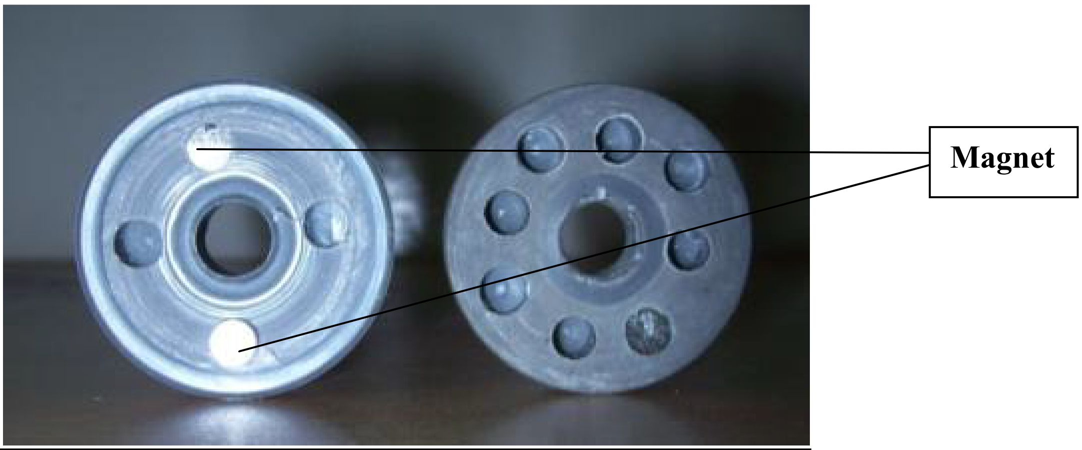

Figure 4.6: magnets placed to the face (surface) of the rotor.

4.4- Manufacturing the stator

In order to optimize a stator design for manufacturing, we have to consider some major specifications related to those models to be manufactured. Those specifications are related to outer and inner diameters of the stator, shape and size of the slots were the windings to be placed. So as described earlier in manufacturing of the rotor approximately it's going to be the same procedure for the stator fabrication. One of the important specifications of the stator that have to be considered while manufacturing the stator is the inner diameter were the shaft that connecting the turbine and the rotor has to rotate freely inside the stator and to make sure that no contact will be between the shaft and the rotor even if misalignment occur will operating the prototype .Further more we have designed the prototypes of the stators to be manufactured with a single difference which is the place where the windings to be settled in . The first prototype designed so that the windings will be placed to the outer circumference of the stator as shown in the Figure 4.7. And for the second prototype as shown in Figure 4.8 the stator manufactured with 4-slots so the windings can be placed in.

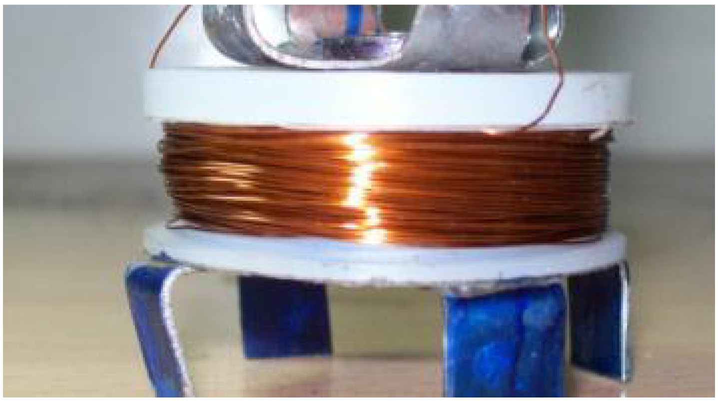

Figure 4.7: Windings around circumference of the stator.

Figure 4.8: Windings are placed in the stator slots.

So for the two designed stators the factor that will be changed to record its results, is the number of the winding turns which will be changed for different number of turns for each design to optimize the best results and came out with the best fabricated design.

4.5- Coil

The most important consideration in winding specifications is wire size, number of turns, winding specifications. The final design element that will determine the power output of the device is the coil. Three variables affect the coil's ability to convert magnetic flux lines into current, position of the coil relative to the flux, size of the coil, and composition of the coil. In order to maximize the number of flux lines that pass through the surface of the coil, the cross-sectional area of the coil must be positioned perpendicular to the magnetic flux lines emanating from the stator magnets. Both the cross-sectional area and the length of the coil also affect the coil's ability to conduct. In the process of choosing the best wire thickness for the design we used an iterative process to find the best wire thickness that can produce the higher induced current in the windings so that started the iteration process for a wire with a thickness of 1.2 mm down to 0.2 mm. And through experiments we found that the best wire to choose was the wire of 0.2 mm thickness with the minimum resistance that was a bout 7Ω that came with the best results of the output voltages.

4.6 Rectifier:

A rectifier is an electrical device, which convert alternating current to direct current, a process known as rectification. Rectifiers are used as components of power supplies and as detectors of radio signals.

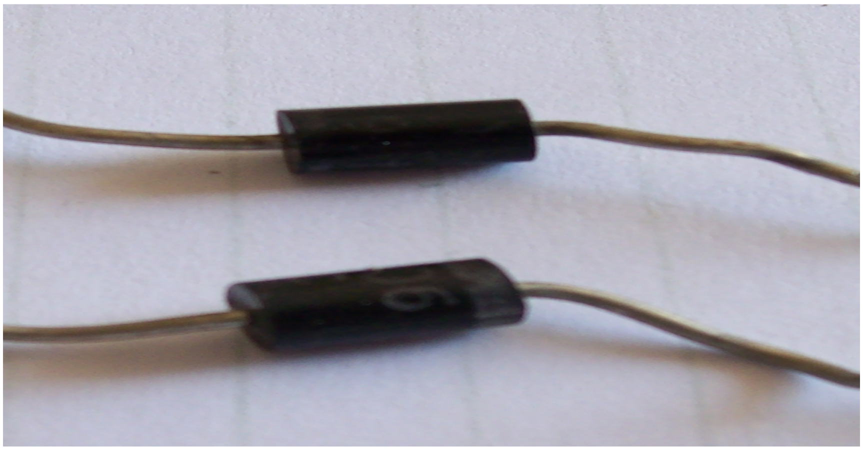

Figure 4.9: Rectifier used to convert AC / DC.

Rectifiers may be made of solid-state diodes, vacuum tube diodes, mercury arc valves and other technologies. When just one diode is used to rectify AC (by blocking the negative or positive portion of the waveform) the difference between the term diode and the term rectifier is merely one of usage, e.g., the term rectifier describes a diode that is being used to convert AC to DC. Almost all rectifiers comprise a number of diodes in a specific arrangement for more efficiently converting, AC to DC than is possible with just a single diode.

4.7 Digital tester:

In this work we use a high performance digital DC/AC (yokogawa 2343), tester which in the figure 4.10 with 4-digits. In addition to capabilities, frequency test, temperature, peak hold, and data hold.

Figure 4.10: Digital yokogawa tester.

The response time 2 seconds to rated accuracy from 10% to 100% of 4000 counts and its rated accuracy within ±1.0%.

4.8 Tachometer:

A tachometer may come in different designs yet is used for one purpose. This instrument measures the rotation speed of a shaft or disk which is commonly found in motor and other machines. In other words for simpler understanding, tachometers are utilized to measure the rotating speed of any device which are ran mechanically. For our information, In this experimental setup a digital tachometer shown in figure 4.11 used to Record the speed of the rotor. This device is also being utilized in some experimental aspects.

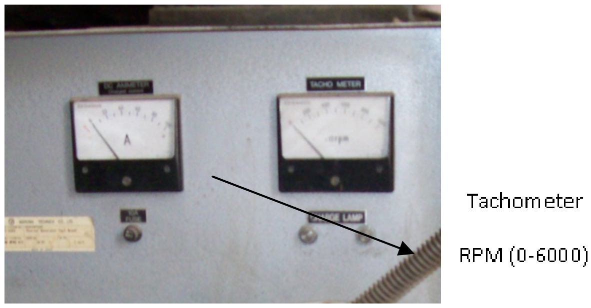

Figure 4.11: Tachometer for testing the revelation per minute.

When generator runs, a potential difference or voltage will generate between the terminals of the motor. The generated voltage is directly proportional to the r.p.m. of the generator.

4.9 D.C Power Generations

After the open-circuit voltages were measured, various tests were performed to demonstrate power generation. First, various load resistances were connected to a single phase of the machine in order to confirm the results. These tests demonstrated AC power generation and confirmed that the 4-slots of windings yielded the highest output power. However, AC power is not desirable in a portable power system because almost all modern portable electronic devices require a DC source. Thus, a power conversion circuit was implemented to enable DC power generation as shown in Figure 4.12.

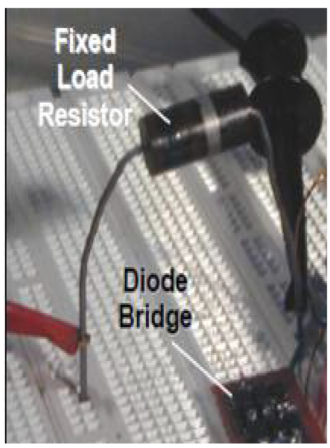

Figure 4.12: power electronic circuit.

4.10 Testing

Once the manufactured prototype is assembled, it is placed to the test bench as shown in the Figure 4.13.

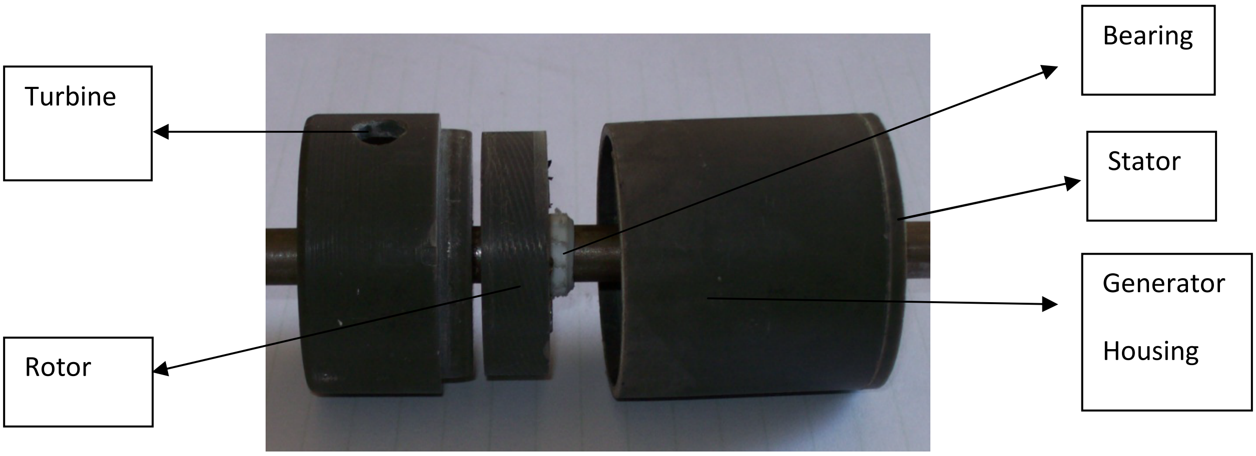

Figure 4.13: Assembled prototype to be tested on the test bench.

The necessary devices to run the experiments are attached one device are the compressed air source. When the compressed air starts to inter to the turbine through the inlet hole the turbine blades will start to rotate and consequently the rotor will start to move approximately at the same speed a different number of magnets inserted to the rotor and those inserted magnets will rotate right above the stator windings that placed at the stator slots. The first step before start recording results from the prototype is running, the system to make sure all the parts are working efficiently and to test the speed senor and the digital tester are recording correctly. After that the experiments are started by directing compressed air toward the turbine and controlling the harvester rotational speed using a pressure gage of Figure 4.14 of the shaft which can be recorded from the speed tachometer, the system will be test for a speed ranging from 0-6000 rpm.

Figure 4.14: compressed air pressure gage.

The goal of this phase of experiments is to find the minimum speed at which the system will start to produce power. Thus running the experiment with different parameters, the minimum speed found to be at least 150 rpm. The current induced in the wire windings due to the movements of the magnets of the rotor over them can be measured. The stator windings as shown in Figure.4.15 were ranged from 1 to 500 turns per stator slot and changed for each system test.

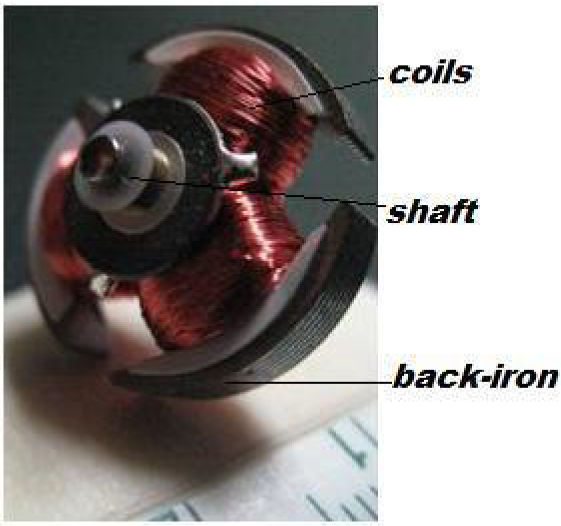

Figure 4.15: stator windings with back-iron inserted.

The results was recorded to find the best number of windings that can harvest the maximum output power from the manufactured System and her come the second

goal of this experimental work which is finding the minimum number of the winding that the system can start work efficiently . Through the experiments it was found that minimum number of the windings per stator slot is 50 turns per slot. During testing there was three source of data, output voltages that measured from the generator velocity that can be measured from a speed sensor and the number of magnets that inserted to the rotor, from all the data only the output voltages had to be processed. The other data values such as speed values were written into tables for each speed test, the output voltages was increased significantly as we increase the speed. The tests was continuous and lasted for more than two hours for each set up in order to change the variables that effect the performance of the manufactured prototype. The number of magnets to be inserted to the rotor, number of winding turns to be fed to each slot of the stator. In this way, there was a main start point for each test and sub starting points for the output voltages an example is given here from the recorded results, for a speed of 150 rpm at 6-magnets inserted to the rotor with 900 turns of windings the output voltages was 0.08 V. The output voltages and the power generated from the system was recorded for different speeds starting from 150 rpm which is the lowest speed that the system start to generate power up to speed of 6000 rpm which is the maximum speed that the system can operate with. The last parameter to be studied is the effect of inserting the back-iron to the system either it's add to the stator or to the rotor and how such an addition will affect the output voltages of the designed system. In this chapter results shown with some explanations the reader should keep in mind the main objective of this work ,which is to develop an experimental generator in the size of meso-scale (centimeter) with the maximum output power can be harvested from that system. Tests were conducted to many manufactured prototype and the parameters that control the

output voltages of the design changed for each and single experiment and the results recorded for every time a new experiment will be preformed the parameters changed for example (number of windings, number of magnets). With these prototypes the operational results generated by the developed experimental design tool have been verified. The prototype machine is an axial-flux permanent-magnet machine with one-rotor-one stator configuration; the stator is assembled electrically in series by default. The nominal power of the machine is milliwatt to watt and the maximum rotational speed is 6000 rpm. The magnets are Neodymium-Iron-Boron magnets which are glued on the surface of the Teflon rotor disk. The constructed prototypes allow for future modification of the machine structure without having to consider excessive machinery. The rotor schematic, allows changing the magnets without having to remanufacturing the rotor disk because the magnets are initially glued to additional rotor holes. As shown in Figure 4.16.

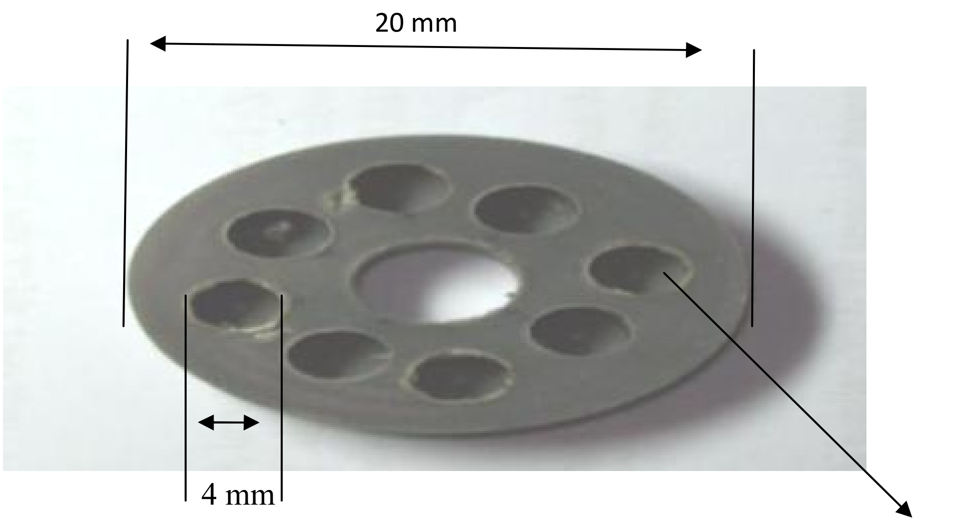

Figure 4.16: Rotor schematic.

This allows the investigation of the effects of different magnet numbers on the output power. If required, the whole rotor disk may be changed without changing the shaft since the rotor disk is fixed to the shaft via bolted joints. However, if unbalanced loading occurs between the stators due to the manufacturing tolerances, the net axial force affecting the rotor structure is not necessarily equal to zero. In order to align the rotor exactly above the stator, a special bearing arrangement has been introduced. The bearing, located between the ends of the rotor and the stator, make it possible to control the rotor position inside the machine without opening the frame. This structure is thus suitable for purposes when the influence of the rotor misalignment on the performance of the machine is to be studied. The stator of all prototypes was manufactured from Teflon material with conventional lathe and CNC machines, and is fixed to the shaft using bolt joints. Each of the stators has 4 slots. One of the machine stators is shown in Figure. 4.17 Before and after winding being placed to the stator.

Figure 4.17: Stator before and after windings.

Each of the 4-slots has different number of turns where the maximum number of turns is 500 per slot. Both ends of the phase windings of the stators are available in a connection box. This, as a result, allows possible changing of the machine's electrical connection from a star connection to a delta connection also changing the connection between the stators from parallel to series connections. The machine is

designed to operate in series connection while it is possible to run in different modes by modifying its operating point. While in operation a spinning rotor with alternating magnetic poles generate a time varying magnetic field, which induce AC voltages in the stator windings that are positioned underneath the rotor (Faraday's law). When the winding terminals are connected to an external load, the device generates electrical power. PM meso-generator dimensions varying in size from 20-mm to 40-mm in the rotor diameter have been reported with output power ranging from milliwatt to watt. While avoiding the design and fabrication complexities and integration within a teflon generator structure.

Chapter 5

Experimental results

5.1 Experimental results

The most interesting part of any experiment is the data that is gathered from it, whether it validates a hypothesis or brings a new puzzle to light. Just as the miniaturized design, process is an iterative process, so are the results from experimentation used to refine the initial design. The results from these experiments are detailed below and they show great promise for this design. Some parameters that explained earlier had to be changed every time the prototype is being placed to the test bench. The starting point for testing those prototypes is as follows, the number of magnets that the system can operate at least with two magnets with two stator slots and with minimum number of winding turns is 50 turns per slot. So the table below describes the minimum requirements needed to start testing the system.

Table 5.1: Minimum requirements needed to start testing.

Number of magnets	Speed(RPM)	Number of stator slots	Winding turns/slot
2	150	2	50

For the first test on the prototype, the parameters were set as follows: the number of winding turns is 50 turns per slot, with coil resistance about 7Ω, number of magnets is two magnets being inserted to the rotor. Each design tested twice once without the back iron being inserted to the stator windings and second test with

the back iron inserted to the stator slots. The results presented in Figure 5.1 show output voltages of the first manufactured design for the identified parameters above.

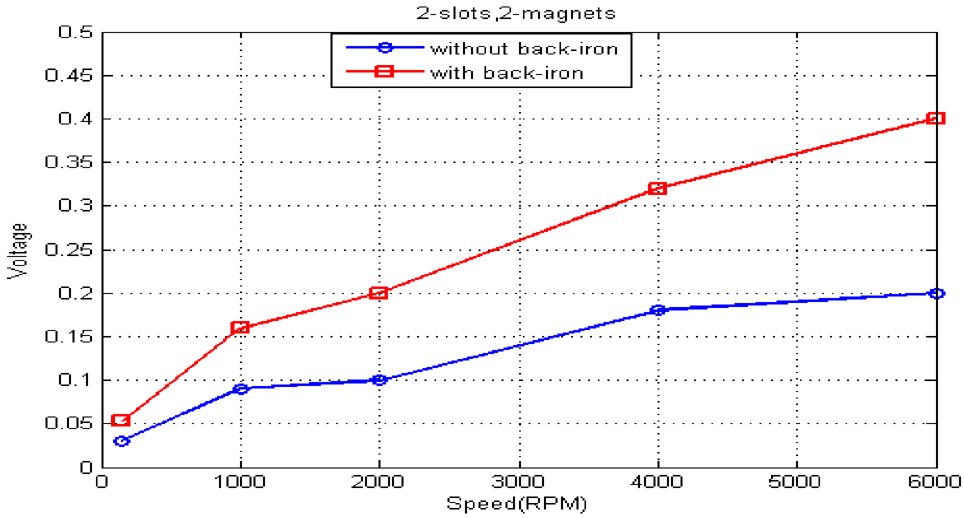

Figure 5.1: Experimental results for 50 turns winding via speed.

The system shows the minimum output voltage of the system without back-iron being inserted to the system is about 0.03volt with two magnets at the rotor operating at 150 rpm and the maximum output voltage of the same system is about 0.2 V at 2-magnets at the 150 rpm and those results is without the load being attached to the winding coils. While for the same design we can notice a good improvement in the obtained results from the system after inserting the back-iron to the stator windings which record a minimum output voltage about 0.16 volt with two magnets at 150 rpm and a maximum output voltage about 0.4 volt at the same speed and number of magnets with output power of 0.75 milliwatt at load condition.

As shown in the figure 5.2 another type of comparison between number of magnets and the output voltages from the extracted results and how the increase in the number of magnets will induce more voltage in the windings and as well effect the output voltages of the tested system as its obvious from the figure that the maximum harvested power from the system at 2- magnets record about 1.3 volt at 6000 rpm and at the maximum performance of the system was about 1.7 volt at 8-magnets at the same speed.

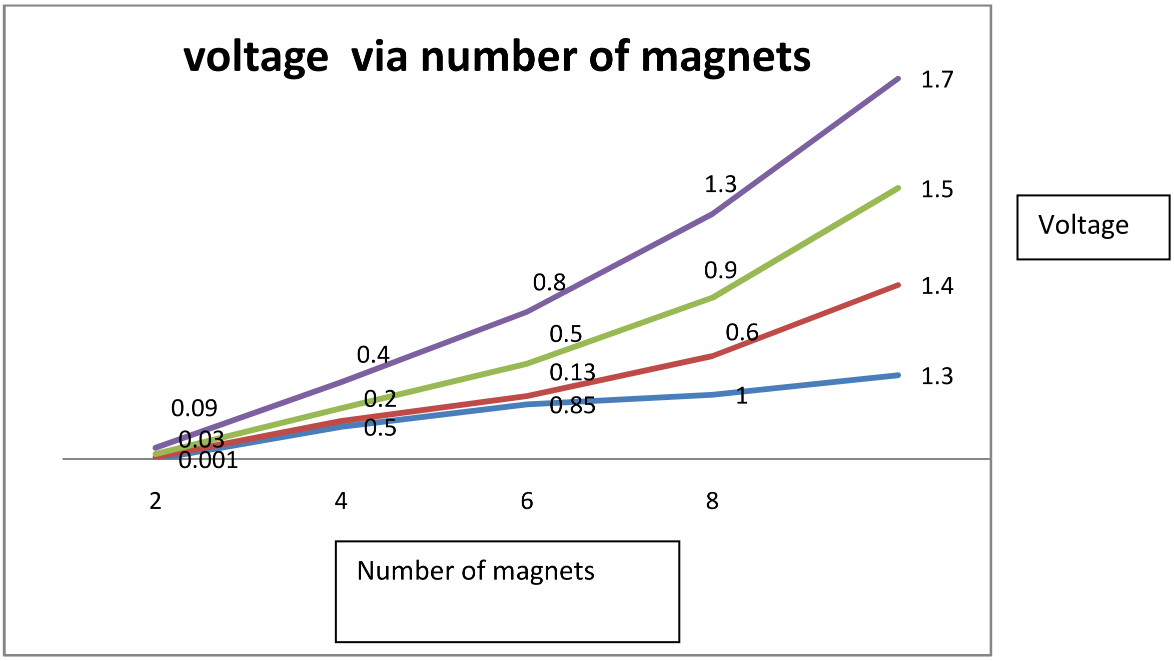

Figure 5.2: Output voltages via number of magnet.

And the effect of the speed can be noticed from the figures because most of the results nearly close to each other at the starting speed which is 150 rpm.

Now as it has stated before about changing the parameters and record their effect on the design one parameter is chosen to be changed while maintain the other parameters fixed. For this phase the number of magnets is the one to be changed starting from two magnets being inserted to the rotor and ending with eight magnets and recording the results obtained. So as shown in the figure 5.3 with 8-magets inserted to the rotor the effect of increasing the number of magnets from two magnets to eight magnets to the

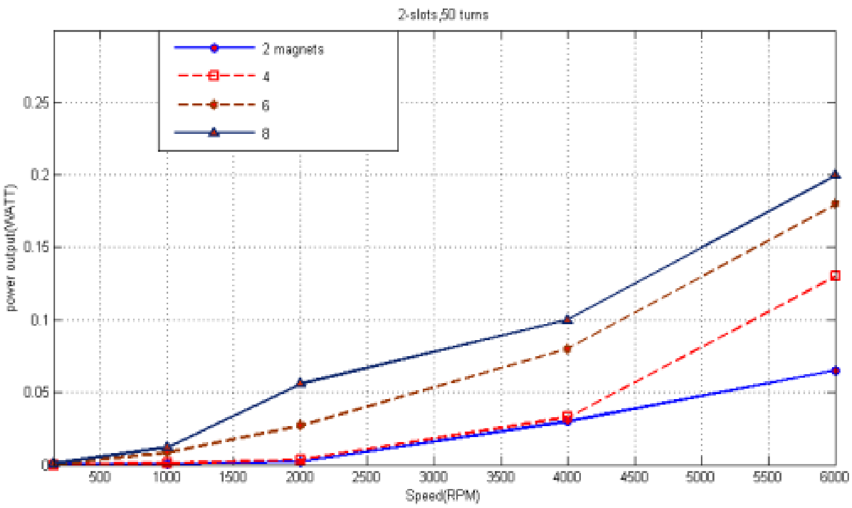

Figure 5.3: Experimental results of 8-magnets via speed.

System affected the output voltages according to the faraday Law of induction so the output voltage increased from 6.5milliwatt to 0.2 volt with an increase in the power output from 8.5milliwatt to 1.4 watt and it should be noticed that those recorded results with the back iron being inserted to the stator windings. Now as a fact from the above results we started to modify the designed prototype to start testing the system by changing another parameter which is the number of stator slots with 4-slots of the stator instead of 2-slots with keeping the number of

windings turns fixed to 50 turns per slot and starting with two magnets at the rotor and start recording the effect of that parameter on the results. Also, in Figure 5.4 the experimental results shows an improvement in the output voltages after increasing the number of slots from 2-slots of the stator to 4- slots while maintaining the number of windings per slot fixed to 50 turns per slot.

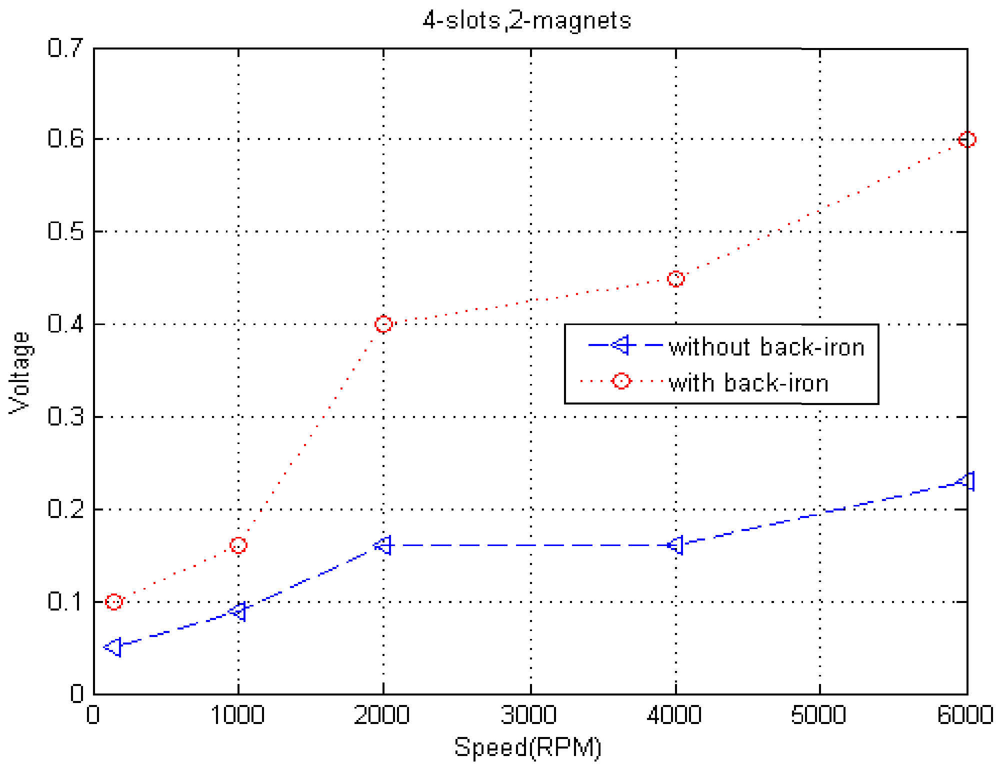

Figure 5.4: Experimental results for 50 turns of winding with 2 magnets.

so the increase in the extracted output voltages induced by increasing the number of slots of the stator is plotting an increase in the output voltages from 0.05Volt to 0.23Volt without inserting the back-iron and from 0.1 Volt to 0.6Volt with inserting the back-iron with no load condition with an output power of 1.3 microwatt at load condition with a speed of 6000 rpm. So for pushing the system to work at the maximum limits that it designed for, the prototype with 8-magnets inserted to the rotor is tested at the same number of windings turns which is 50

turns per slot for 4-slots and tested with and without back iron, and we should notice her that all the results are extracted at the same speeds which is ranging from 150 rpm to 6000 rpm as it was explained previously in chapter four. So for this prototype which tested at a speed of 6000 rpm it plot a result shown in Figure 5.5 of 1.2volt without back –iron being inserted to the system and a 2.1 volt with a back-iron is being inserted to the system recording a maximum

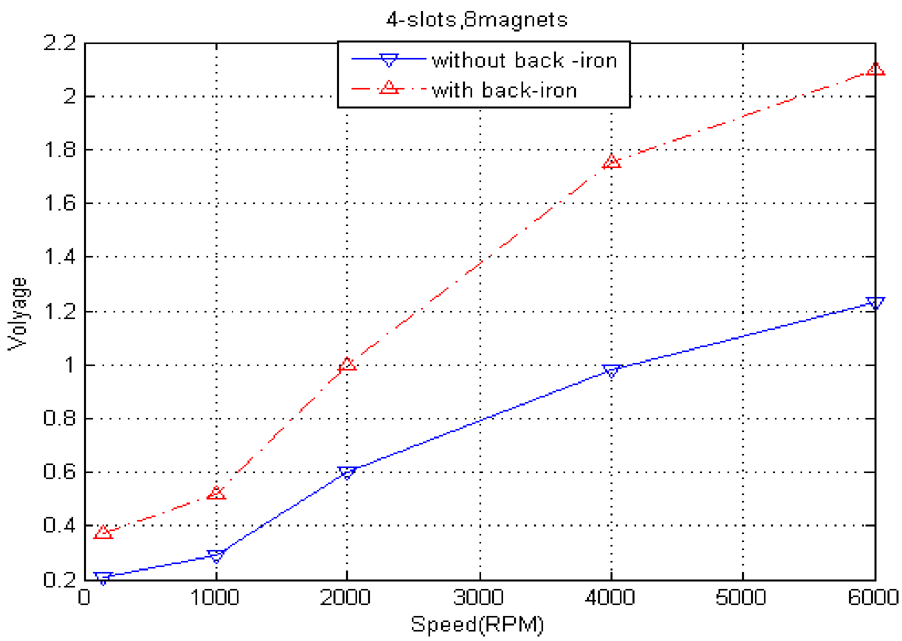

Figure 5.5: Experimental results for 4-slots and 8 magnets with no load.

Output power that can be extracted from the system which is about0.63watt with no load and at 8-magnets but for load condition about 0.45Watt at 6000 rpm. In order to show the effect of the back iron on the power output when it inserted to the stator slots which show a good improvement in the extracted results as shown in Figure 5.6 with keeping the number of magnets inserted to the rotor two magnets and four slots of the stator with 50 turns of winding /slot.

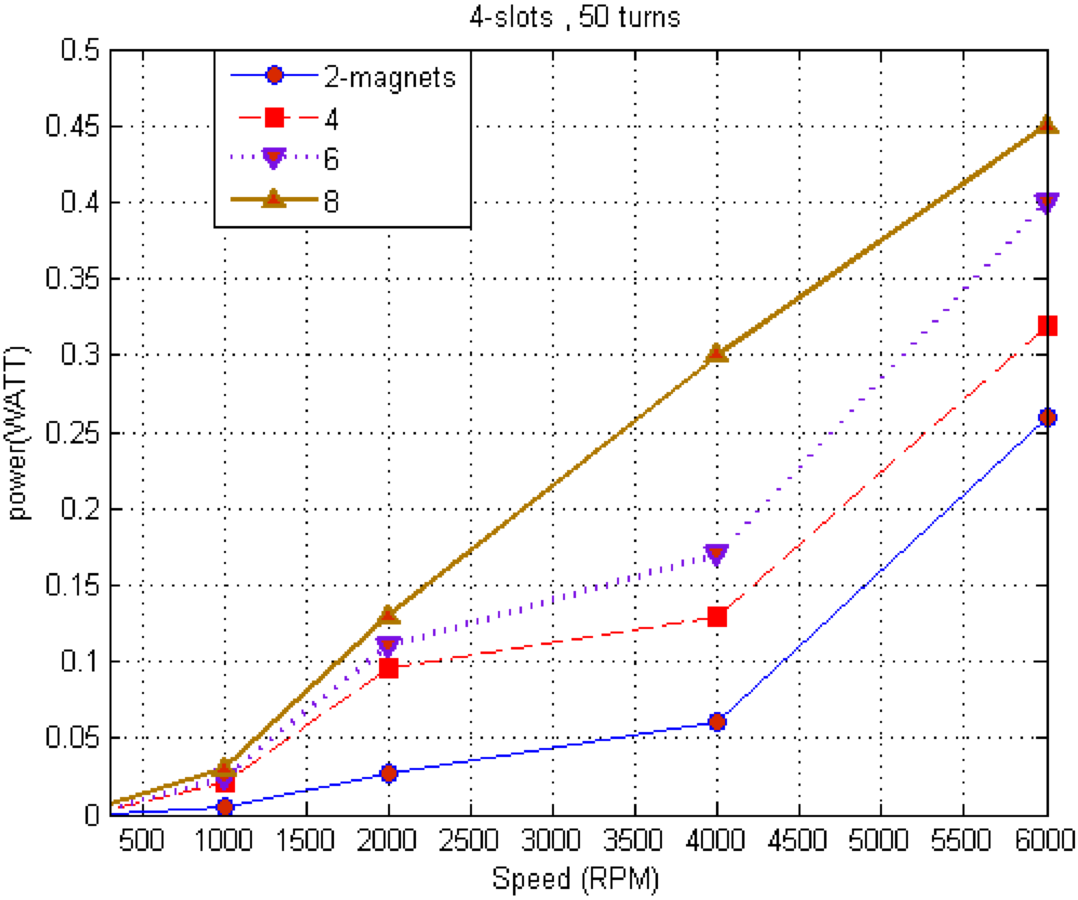

Figure 5.6: Experimental results for different number of magnets via speed**.**

Now in order to study all parameters that effect the generated power from the designed system the number of windings turns will be changed for the prototype and will be raised from 50 turns of winding per slot to 100 turns per slot and plot their effect on the designed prototype as shown in Figure 5.7 the increase in the winding number from 50 turns to 100 turns effected the output voltages from the system so the system plot an output voltage of 2.5V for 2-slots with 50-turns per slot with 8-magnets inserted to the rotor at 6000 rpm without the back-iron being inserted to the system while at

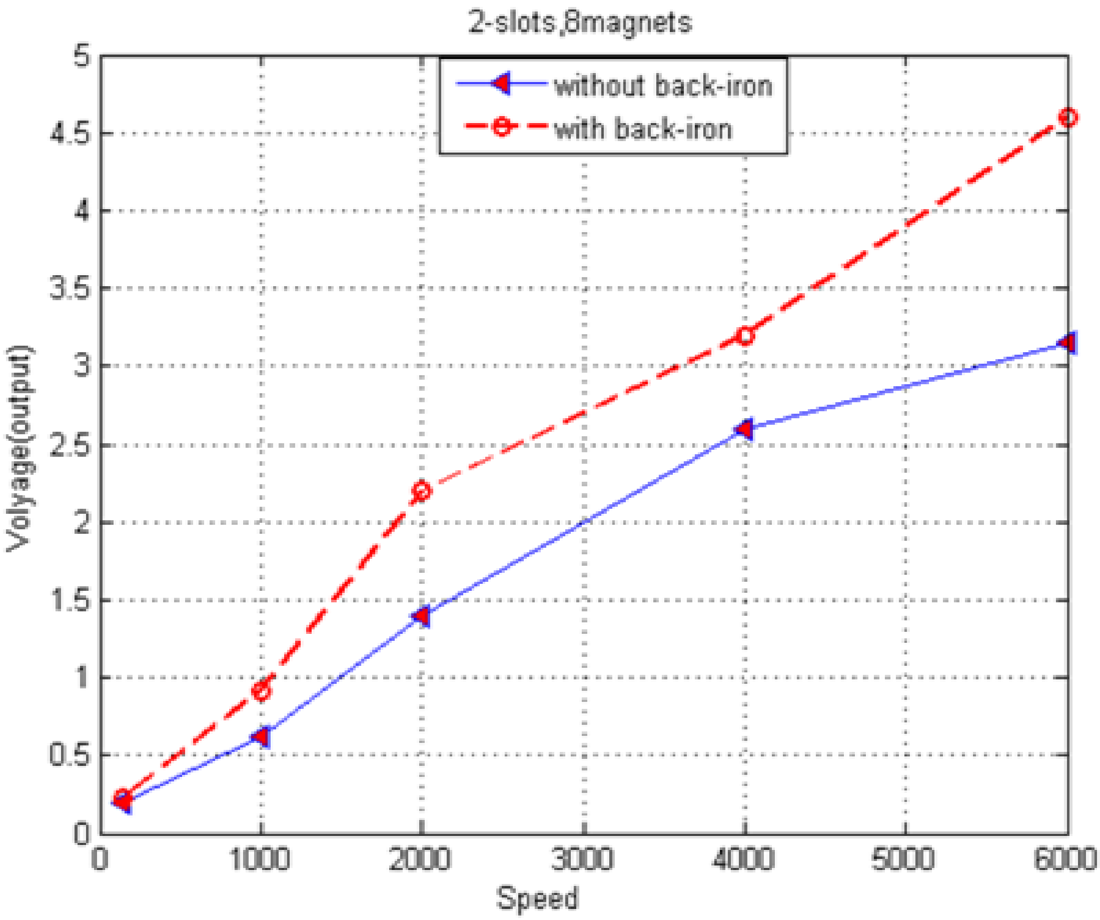

Figure 5.7: Experimental results of 2-slots, 8 magnets.

The same time the system plot about 3.5 volt when the back-iron inserted to the windings of the stator recording a maximum power from the system about 0.4 watts at the same speed. For the same design but with increasing the number of stator slots from 2 slots to 4 slots with 100 turns per slot and with 8 magnets being inserted to the rotor the results came as shown in figure 5.8.

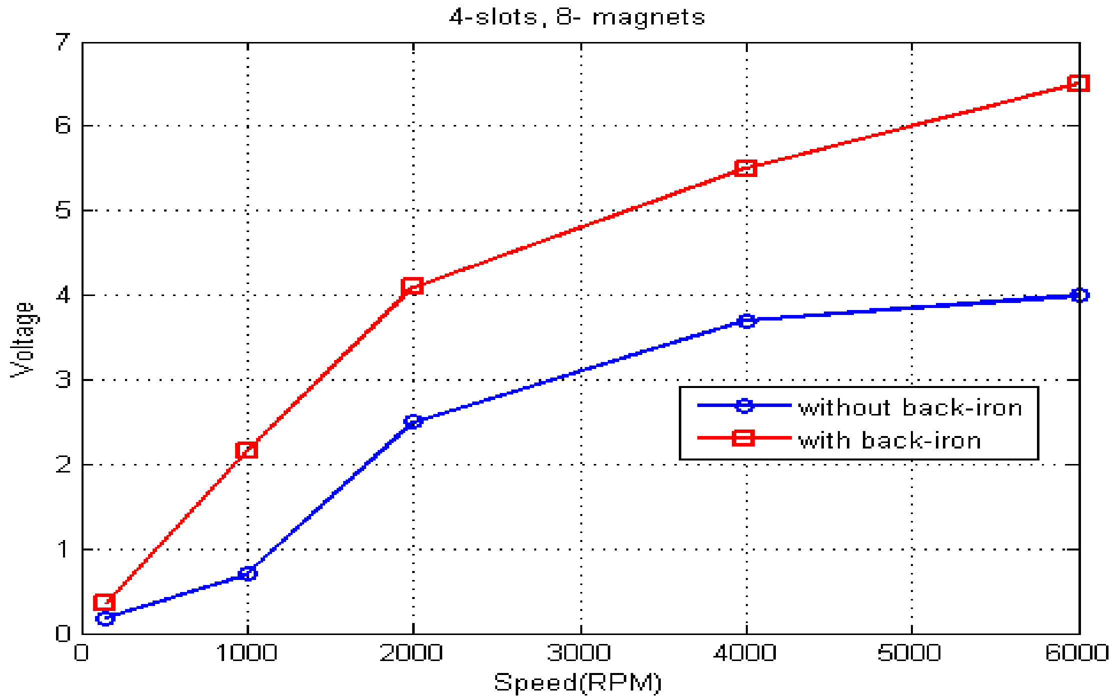

Figure 5.8: Experimental results for 4-slots and 8-magnets.

The system plot an output voltage of 4V for 4-slots with 8-magnets inserted to the rotor without the back-iron being inserted to the system while at the same time the system plot about 6.5 V when the back-iron inserted with no load at speed of 6000 rpm. While for the same parameters mentioned above the system plot about 0.1 volt at 150 rpm and 0.9volt at 6000 rpm without back iron being inserted to the system. While the system recorded 0.25 volt at 150 rpm and 1.3 volt at 6000 rpm with back iron inserted to the system with an output power of 0.05 watt at loaded condition. For improving the results significantly be increasing the number of magnets and number of winding turns per slot and as well increasing the number of the stator slots from two to four and keep tracking the improvement of the output voltages in order to reaches the maximum output

that the system can provide we raised the number of windings from 100 to 300 turns per slot and tested for the same speeds and with a 8 magnets being inserted to the rotor so as we notice the plotted results from figure 5.8. As it's obvious from Figure 5.9 when the number of windings is being raised to 300 turn of winding per slot of the stator for 8-magnets inserted

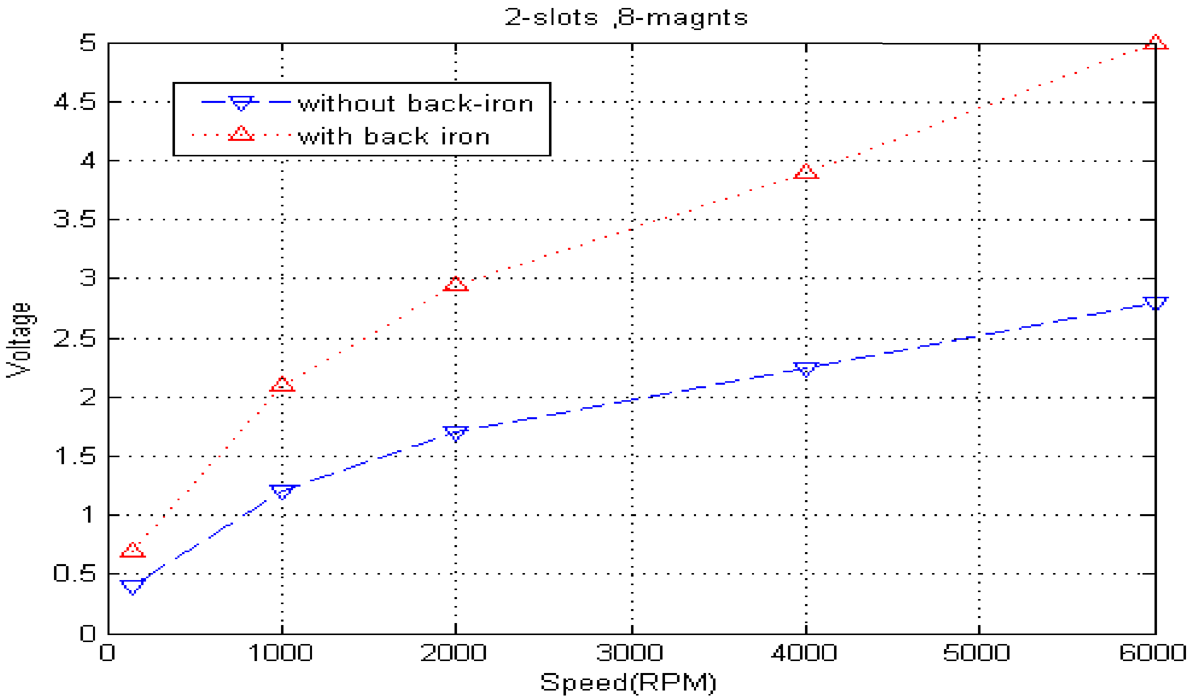

Figure 5.9: Experimental results for 2slots and 8-magnets.

Inserted to the rotor and operating at the same shown speeds the output voltages recorded plot a 2.8V without inserting back iron to the windings and about 5Vwhen the back-iron is inserted to the system and that without load. For more power extracted from the system the number of slots changed from 2-slots to 4 slots with maintaining the number of windings and the testing speeds the same with 8-magnets being inserted to the rotor of generator and the plotted results came as shown in the Figure 5.9.

As shown in figure 5.10 that the maximum output voltage that can be extracted from the system is about 3V at 6000 rpm without the back-iron being inserted to the design and with no load and plotting about 6.8 V at the same speed after the

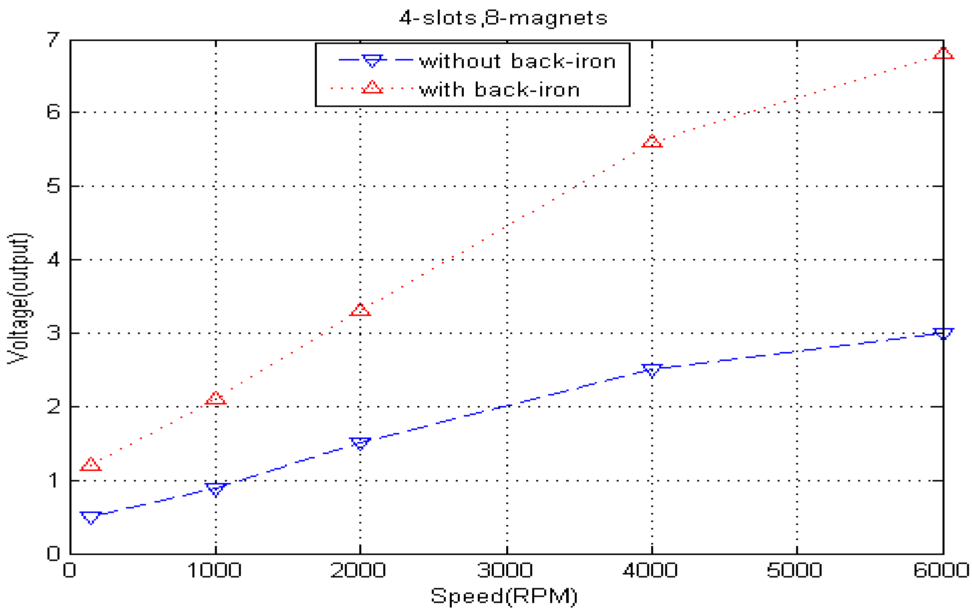

Figure 5.10: Experimental results for 4slots and 8 magnets.

back-iron being inserted to the windings of the stator and also with no load attached to the windings .but when the load is fixed to the system it record about 1.6 volt at 6000 rpm without back iron and 3.8 volt at the same speed when the back iron is inserted to the system with an output power of 0.5 watt at load condition. So when the system came to the final step from changing all the parameters that controlling the manufactured prototypes as has been explained earlier that with 4-slots of the stator and a maximum number of windings that can be placed to the system is 500 turns of winding per slot with 8-magnets being inserted to the rotor. The system was

tested for the maximum parameters that the system can handle and the results plotted as shown in Figure.5.11.

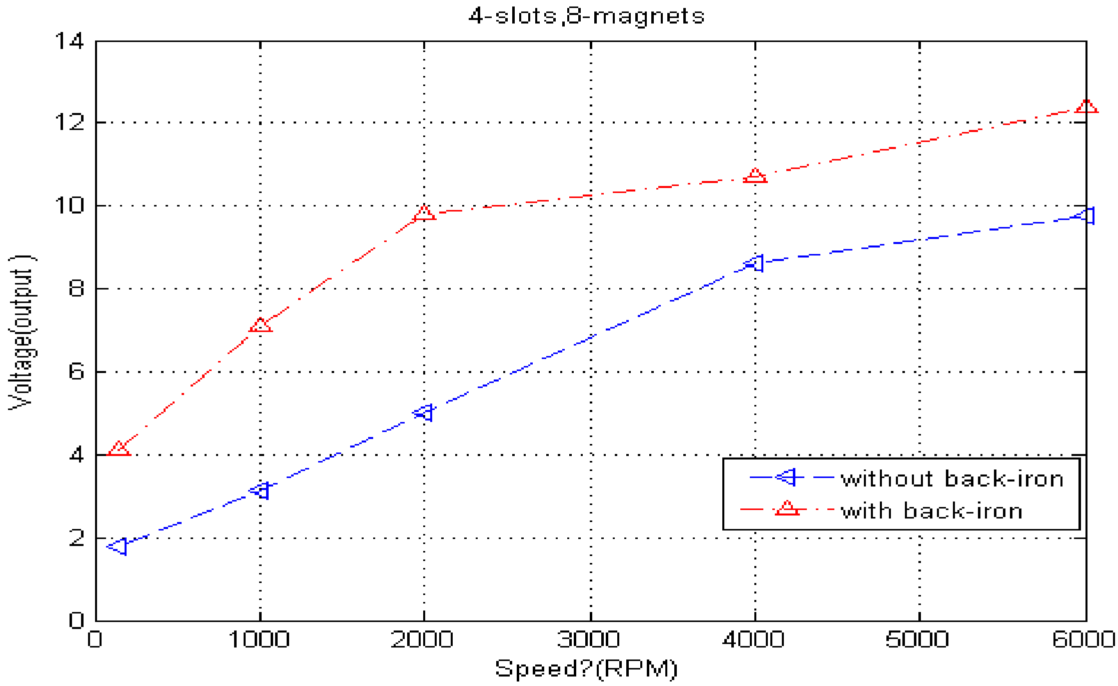

Figure 5.11: Experimental results for 4slots and 8-magnets for 500 turns.

if we changed one parameter and fixing the other parameters to record the effect of changing that variable on the output voltages as we can see from Figure 5.12 that the number of slots and number of magnets are fixed but the number of winding turns per

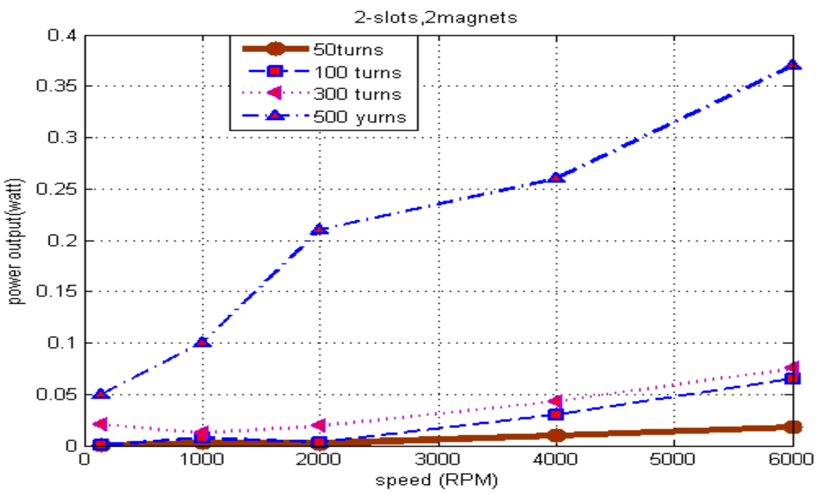

Figure 5.12: Experimental results for different number of winding turns.

Slot is changed from 50 turns per slot to 500 turns per slot and the output power affected in a great part as we can see from the figure 5.12 that the power changed from 2.4μW at 50 turns per slot to 0.38 watt at 500 turns. So for further application of recording the effect of number of turns on the manufactured design the experiment investigated for 2-slots of stator and 8-magnets inserted to the rotor and the recorded results showed in Figure 5.13

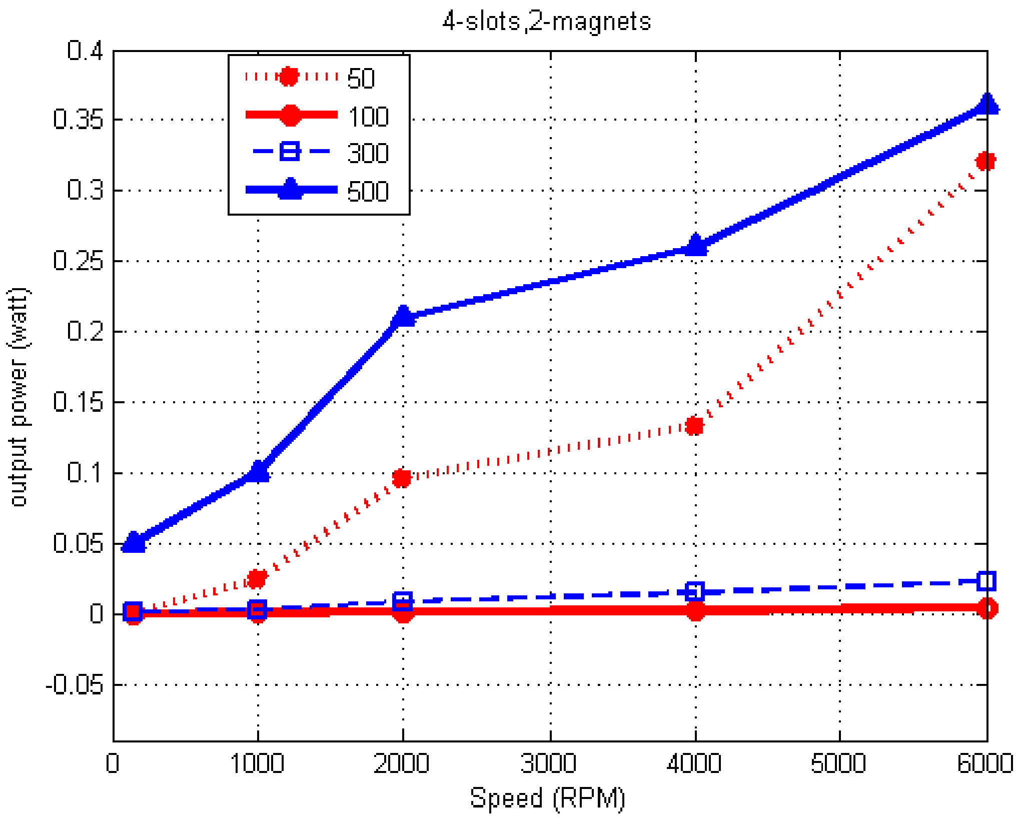

Figure 5.13: Experimental results for different number of winding turns.

Show the great change in the output powers from 0.03 milliwatt at 50 turns per slot to 0.4 Watt at 500 turns per slot at a speed of 6000 rpm so we can conclude that the relation between the number of windings and the out power is linear relation. Now for comparing the output results that indicate the improvement

from changing the number of stator slots from two slots to four slots as shown in figure 5.14 that when we use two slots with 50 turns per slot and with 4 magnets at a speed of 4000 rpm the harvested power from changing the number of slots the power changed from 0.17 watt to 0.78 watt.

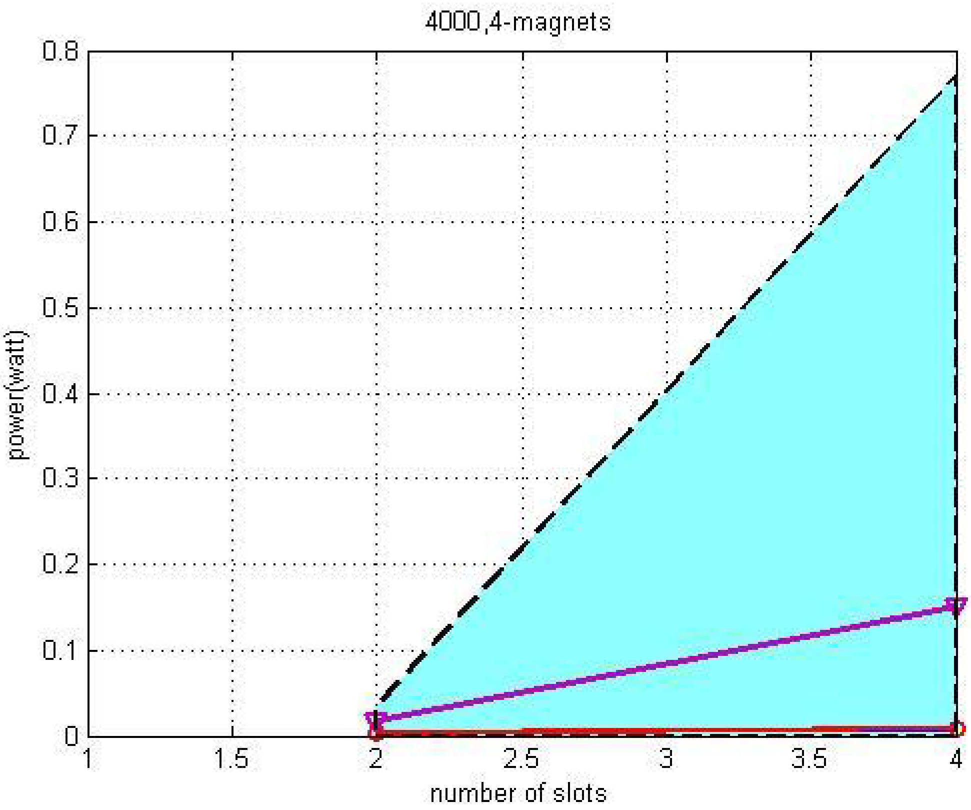

Figure 5.14: shows the extracted results from changing the number of slots to four slots.

Now with another comparison to show the effect of increasing the number of winding turns and the increase, in the harvested power from changing the number of stator slots from 2-slots to 4-slots as it shown in figure 6.15 as its obvious from figure that the increase in power between two stator slots to four stator slots at the same speed and with the same winding turns per each slot.

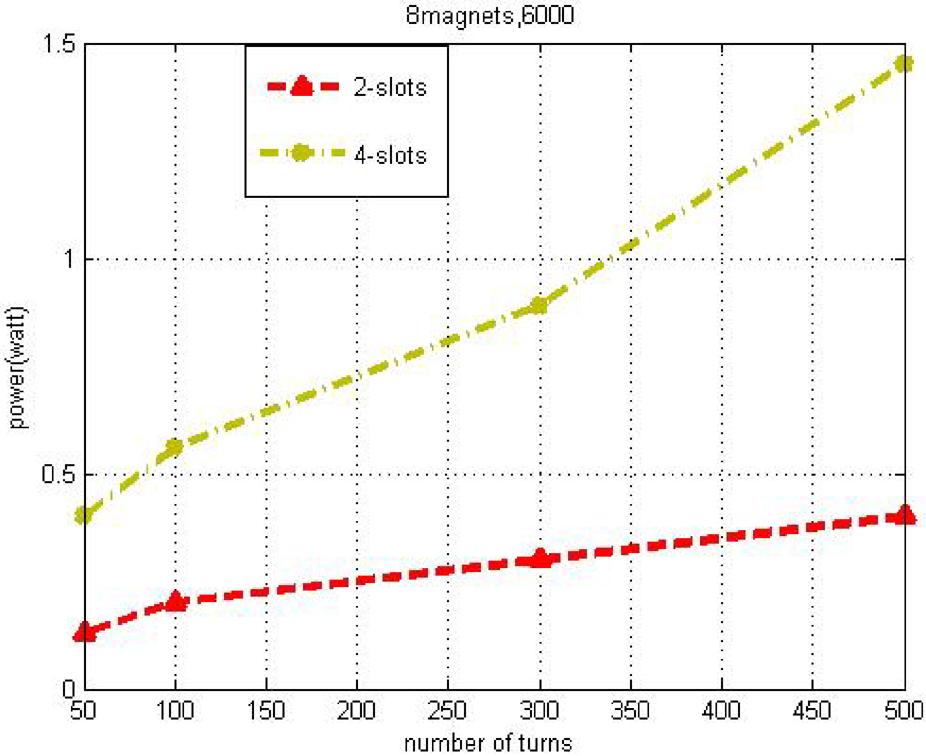

Figure 5.14 shows the change in extracted power from changing the number of stator slots and increasing the number of winding turns per slot.

A shown in Figure 5.15 continuous efforts of optimizing the best design with best output power can be extracted from the system the system has been investigated for 2 slots of the stator for different number of winding turns per slot ,at different rotating speeds with 8 magnets being inserted to the rotor and the results recorded for that prototype was as follows first for 50 turns per slot was about 0.05 watt at 6000 rpm and for 100 turns per slot was about 0.09 watt at same speed and last for 300turns per slot was about 0.2 watt at the same speed, but in the extracted results we can notice a little variation in the recorded results and that due to the current losses in the winding turns which can be overcome by increasing the speed .

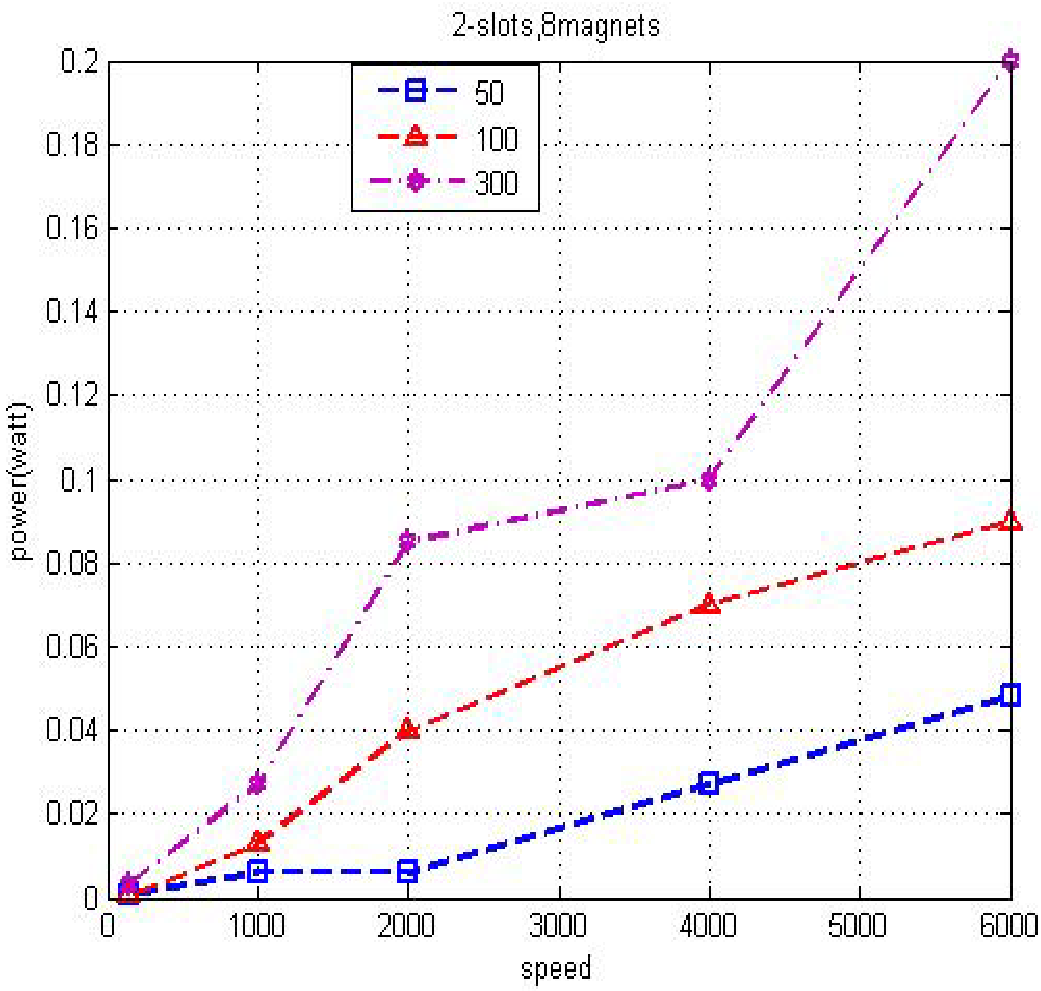

Figure 5.15: show different number of winding via speed.

As shown in Figure 5.16 after increasing the number of windings to 500 turns per slot which the maximum number that can be inserted to each slot with maximum number of magnets which is 8 magnets inserted to the rotor of the manufactured generator the results came as follows the maximum output voltage can be extracted from the system is about 9.7 V and that without the back-iron being inserted to the windings and after inserting the back-iron to the system the maximum output voltage plotted was about 12.4 V and that without load and at 6000 rpm. running the same design at the same parameters but with load condition the results came with 5.9 volt at 6000 rpm without back-iron being inserted to the system and with back-iron inserted to the system,

extracted about 6.6 volt with a maximum output power the system can generate about 1.45 watt As shown in Figure 6.17 the design operate at its maximum performance the design were investigated for 4-slots of stator with 500 turns of windings per slot of the stator with changing only the number of magnets from two magnets to eight magnets with an output power ranging from 0.38 watt at two magnets being inserted to the rotor to maximum output power of 1.45 watt at eight magnets being inserted to the rotor at 6000 rpm and that is the maximum power that can be harvested from the designed generator.

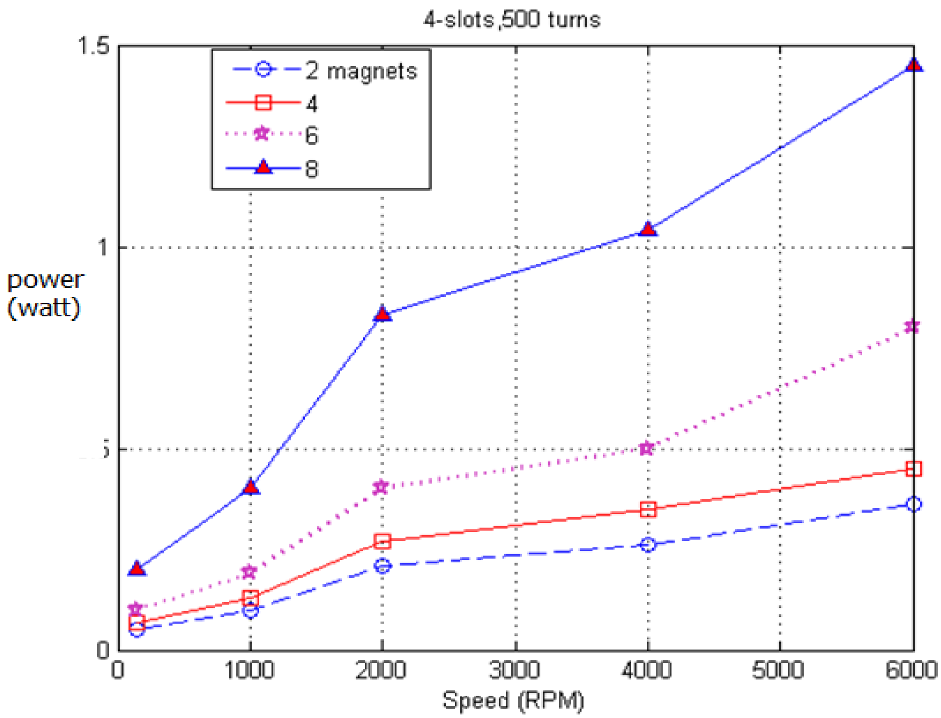

Figure 5.16: Experimental results for different number of magnets.

A full range of data and results can be found in appendix A.

Chapter Six
Conclusion and Recommendations

6.1 Conclusion:

This research began with a goal of developing a new generator in the meso-scale dimension based on the PM machines as a power generation technology. This work has developed an investigation for the effect of the design parameters on the output power generated by the system. Parameters considered are number of windings turns per slot, number of slots of the stator, number of magnets inserted to the rotor and as well the speed (RPM). Continuing the efforts of the previous research to develop that technology in investigating the PM machines to characterize the meso-scale generator, both open-circuit and loaded tests are performed. Experimental phase voltage data as a function of rotational speed was shown. The loaded voltage and power characterizations are performed by connecting load resistors of $R\mathrm{L} = 30\ \Omega$ to the wires. The load is chosen to match the phase resistance, which maximizes the output power delivered. This condition is verified, where the output power of the generator is measured for five resistor sets, and the highest measured power occurs for 30Ω set. The loaded voltage is approximately half of the unloaded voltage, which further verifies the matched load condition. Depicts the output power as a function of rotational speed; the maximum power achieved is 1.45W at a speed of 6000 rpm; the voltage and the output power are linear with speed. Higher speeds could not be achieved due to flow leakage issues and structural integrity problems of the clamped device. These devices prove that the watt level power production is achievable using meso-scale magnetic power generation and demonstrate the viability of scaled PM machines for portable power applications.

6.2 Recommendations

As this part of the project comes to a close, I would like to leave some parting thoughts to any who may continue in this research. Below are my thoughts on what can be done to improve the current device and additional projects that could be integrated with the device to provide a complete system. The results from the experiments taken from this thesis show great potential for the device. The continuation of research in this area should focus on fabrication methods and modifications to the design. Since each of the critical parameters of this device effects the overall power output of the device, there are some modifications that can be made to the design to alter the voltage, and current of the output. This design uses a turbine to turn the rotor and thus generate power. Other designs could be created to make use of a fluid flow outside of the device, more like a water wheel at an old mill. This could be used in larger areas such as inside the heart or the larger blood vessels. Another alternative to either of these designs may be to use the same design for the power generation, but have several stator sets or rotor set to alter the power output beyond the values attainable by simply altering the number of a stator set. as well as studying inserting the back iron materials and their effect on such power generation systems . Regardless of the design used to generate the power, there is still a need to regulate and store the power to ensure a constant level of output. Research needs to be done to design a system that could be integrated with the energy production system to provide a well regulated output for use in the rest of the system. This includes voltage regulation as well as energy storage.

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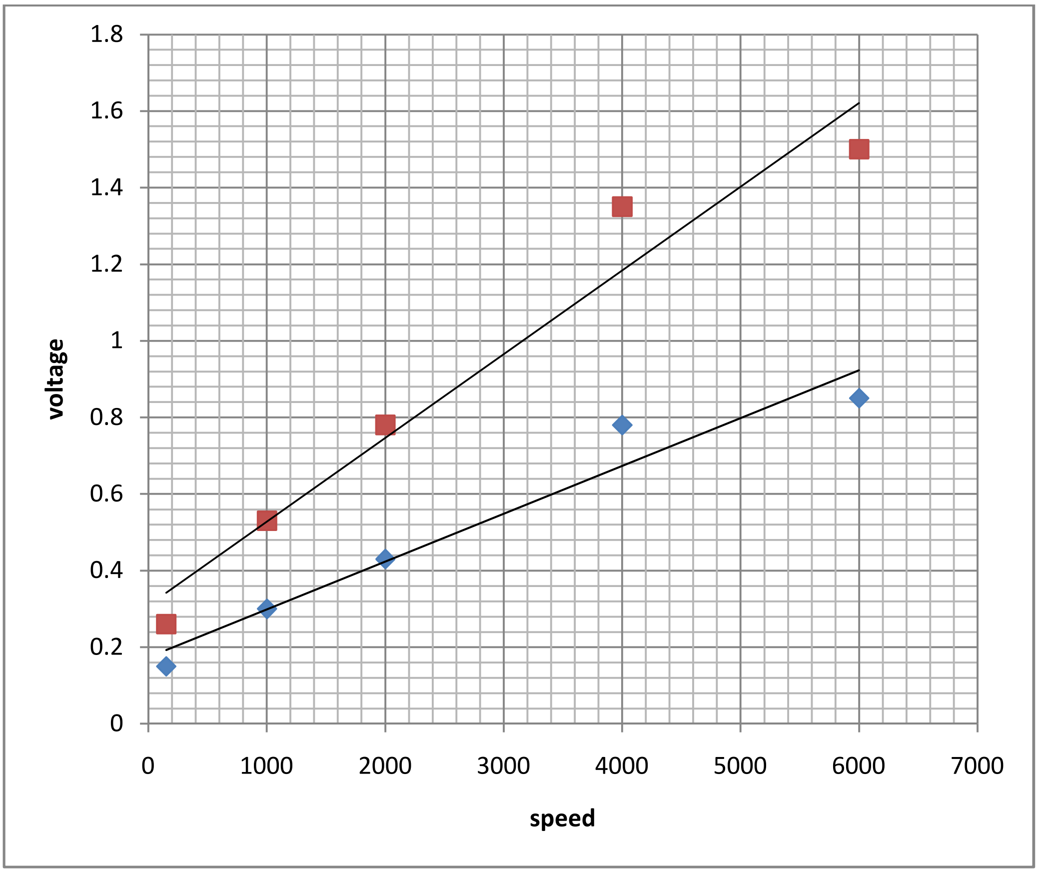
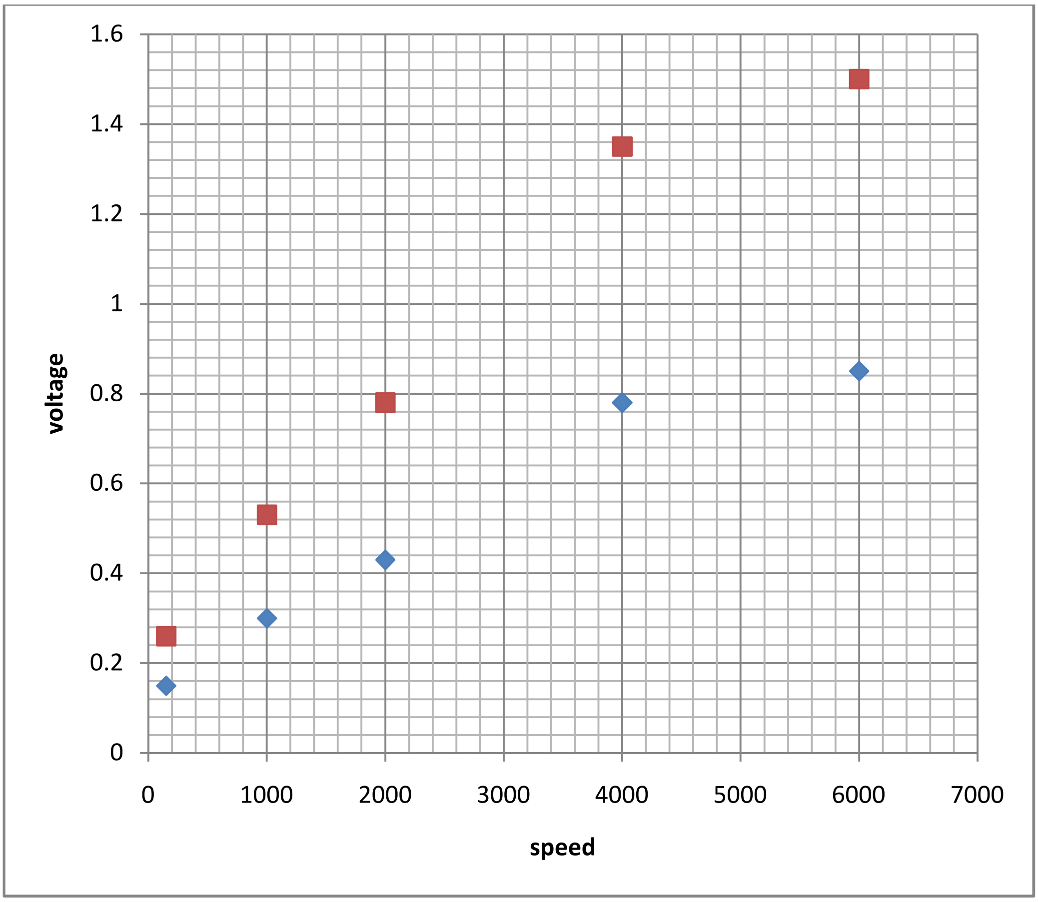
Appendix (A)

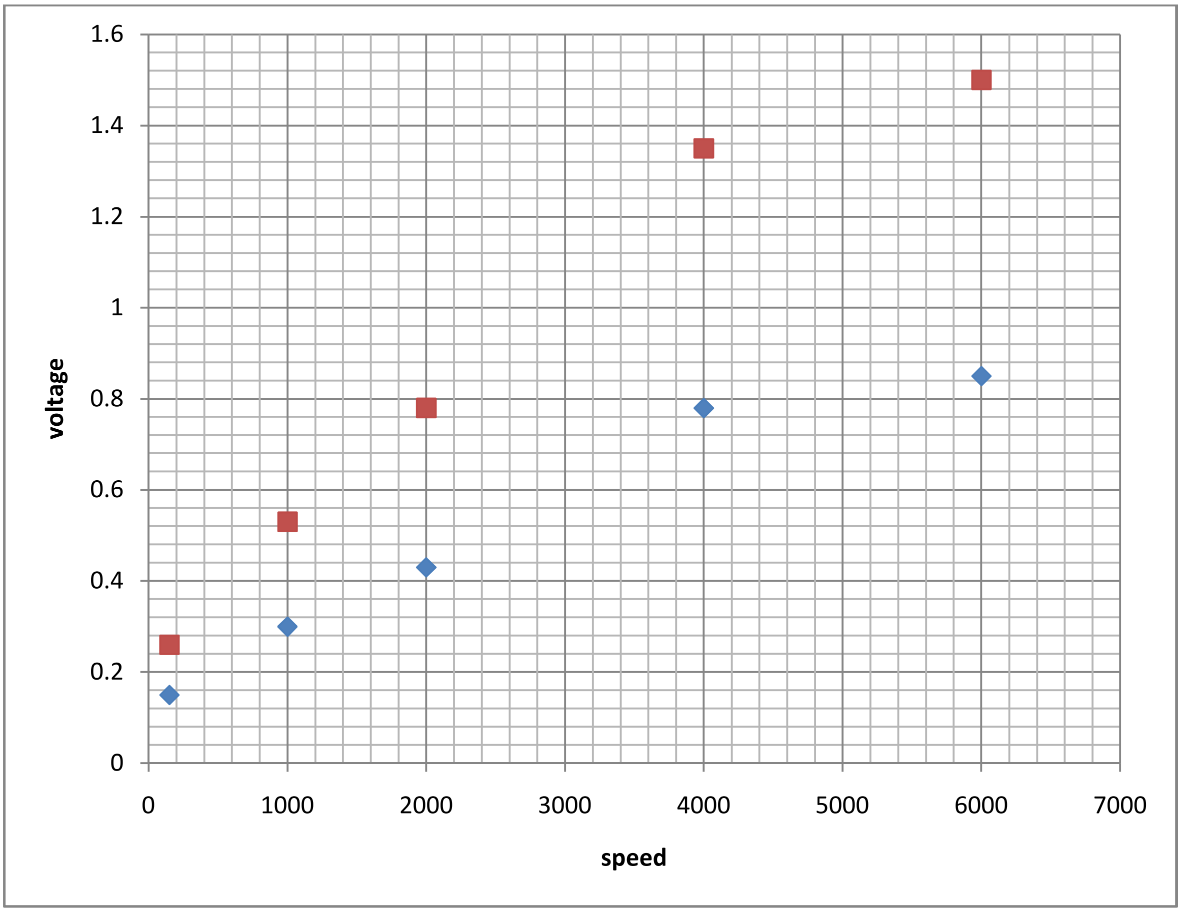
A1: For stator of 2-slots and a rotor of 2 – magnets with back –iron Inserted to the stator with 50 turns with and without back-iron.



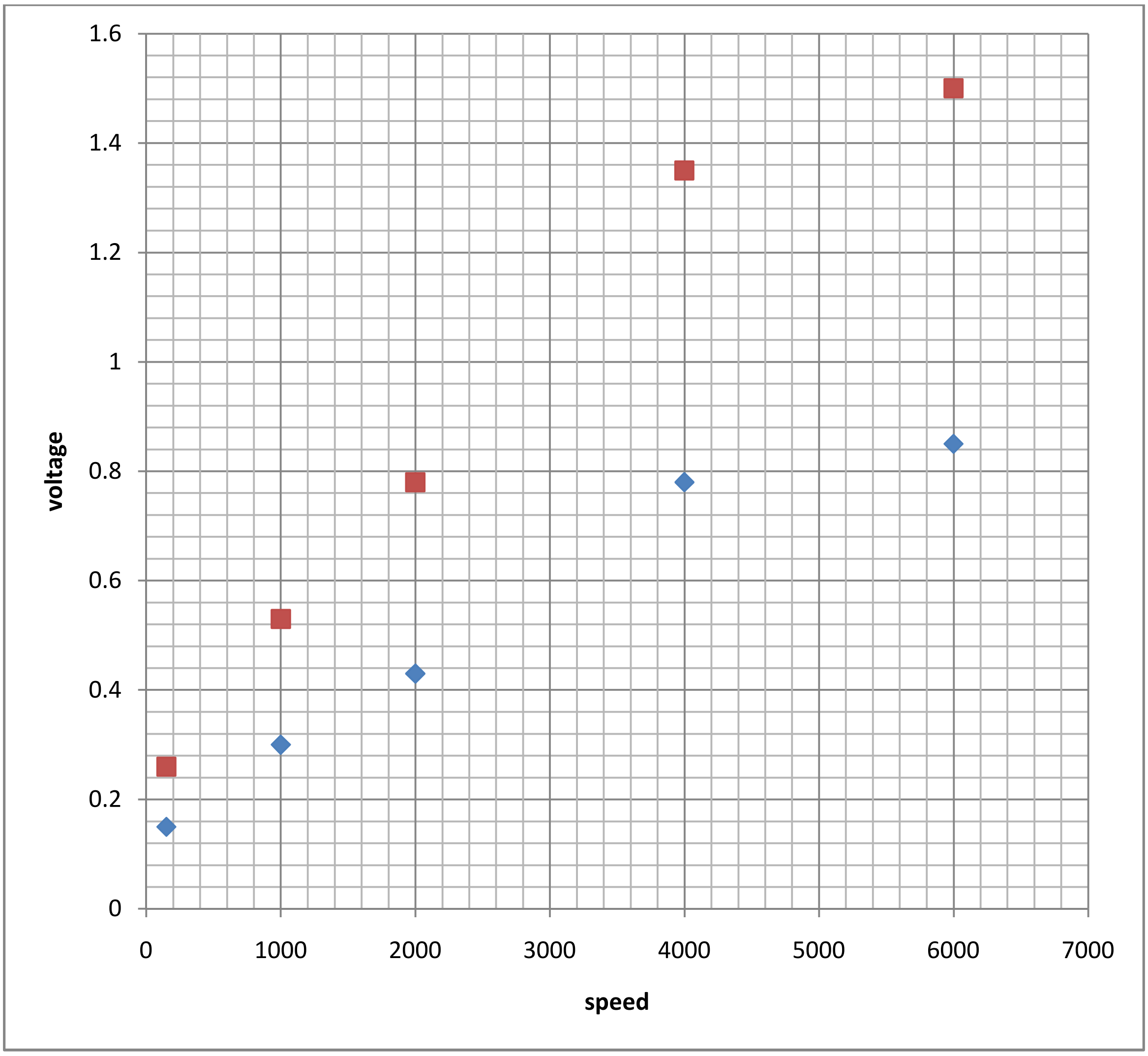
A2: For stator of 2-slots and a rotor of 4– magnets without back –iron inserted to the stator with 50 turns.



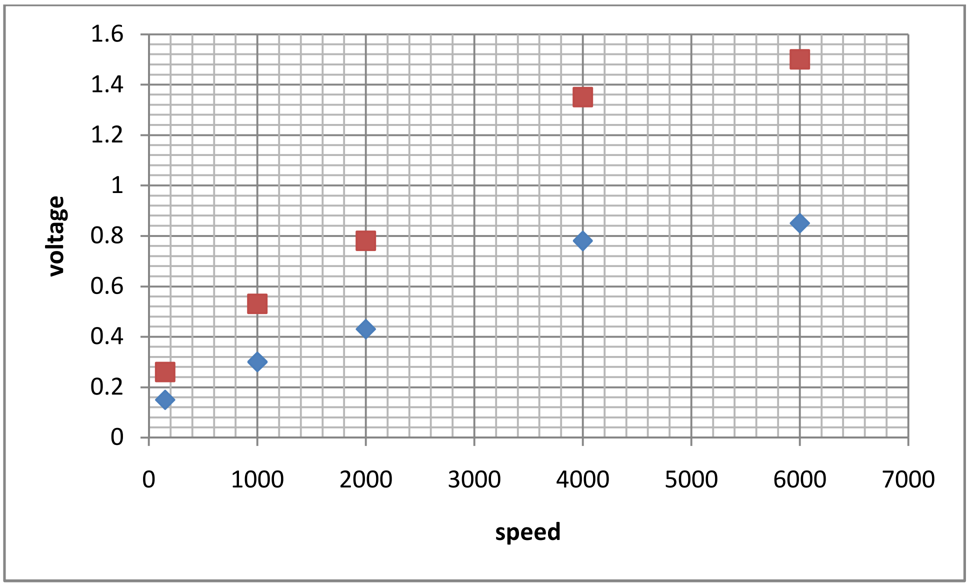
A3: For stator of 2-slots and a rotor of 6– magnets without back –iron inserted to the stator with 50 turns.



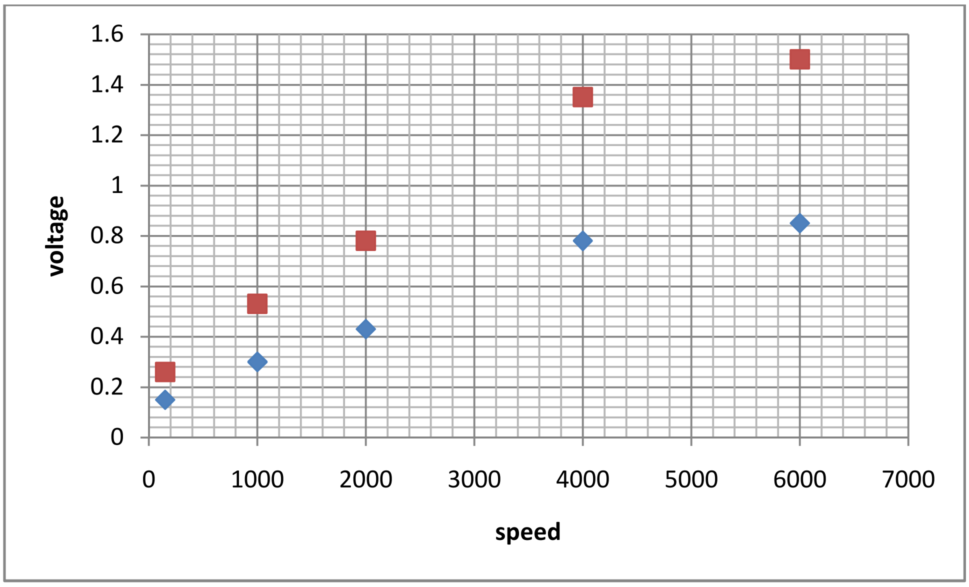
A4: For stator of 2-slots and a rotor of 8– magnets with back –iron inserted to the stator.



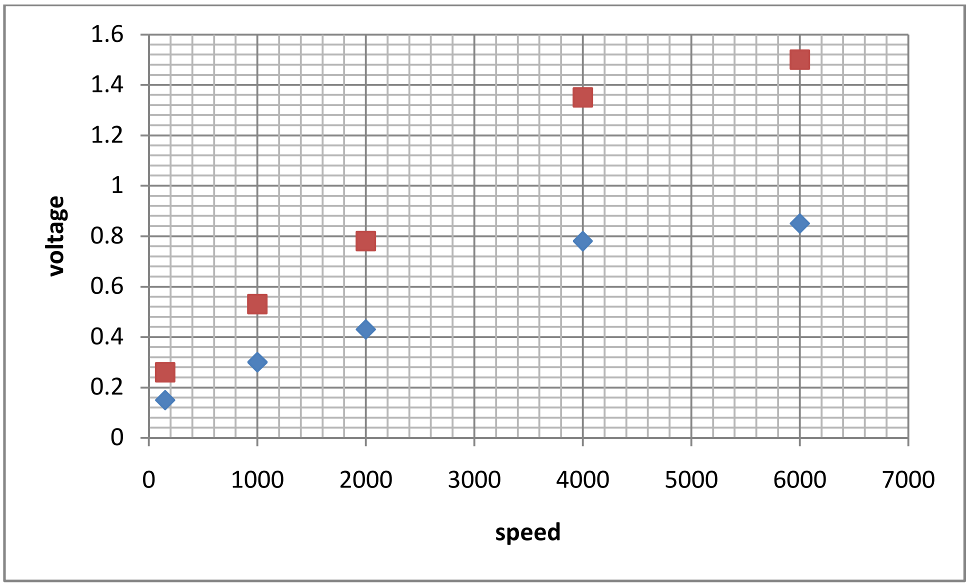
A5: For stator of 4-slots and a rotor of 2 – magnets without back –iron inserted



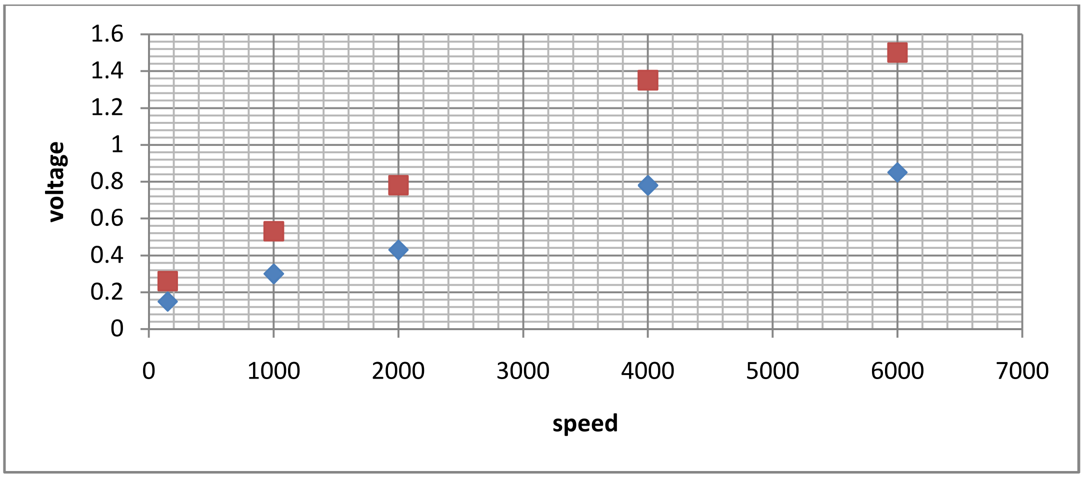
A6: For stator of 4-slots and a rotor of 4– magnets without back –iron inserted to the stator 50



A7: For stator of 4-slots and a rotor of 6– magnets without back –iron inserted to the stator

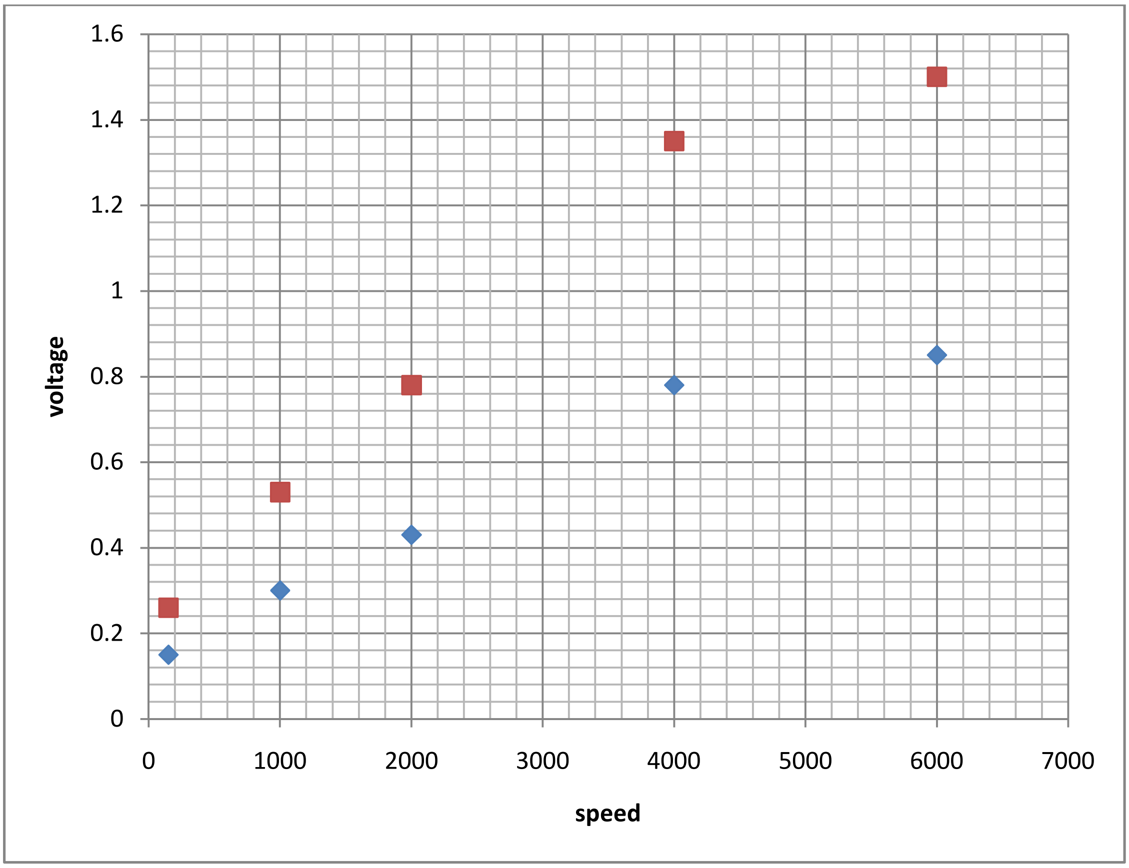


A8: For stator of 4-slots and a rotor of 8– magnets without back –iron inserted to the stator

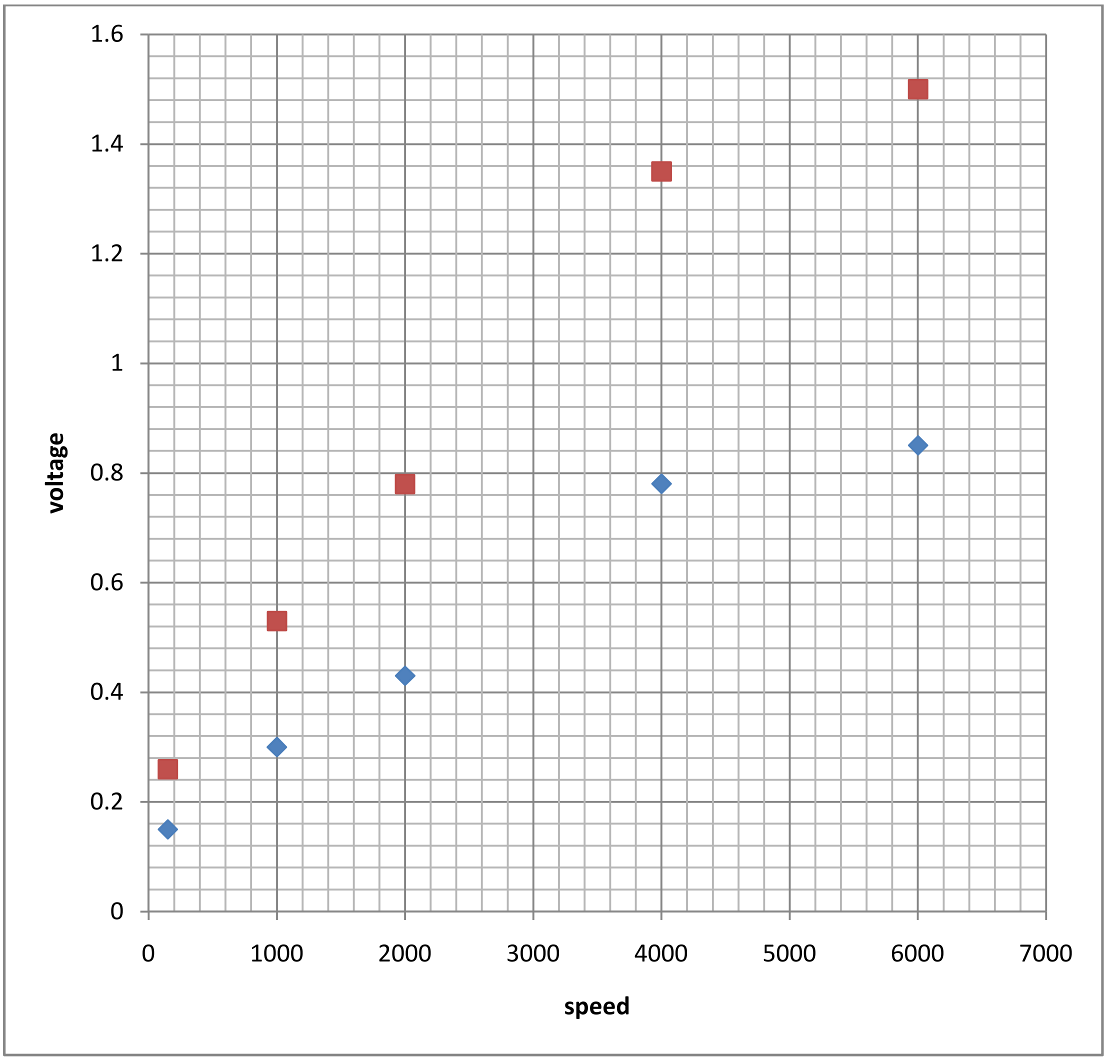


A9: For stator of 2-slots and a rotor of 2 – magnets without back –iron inserted

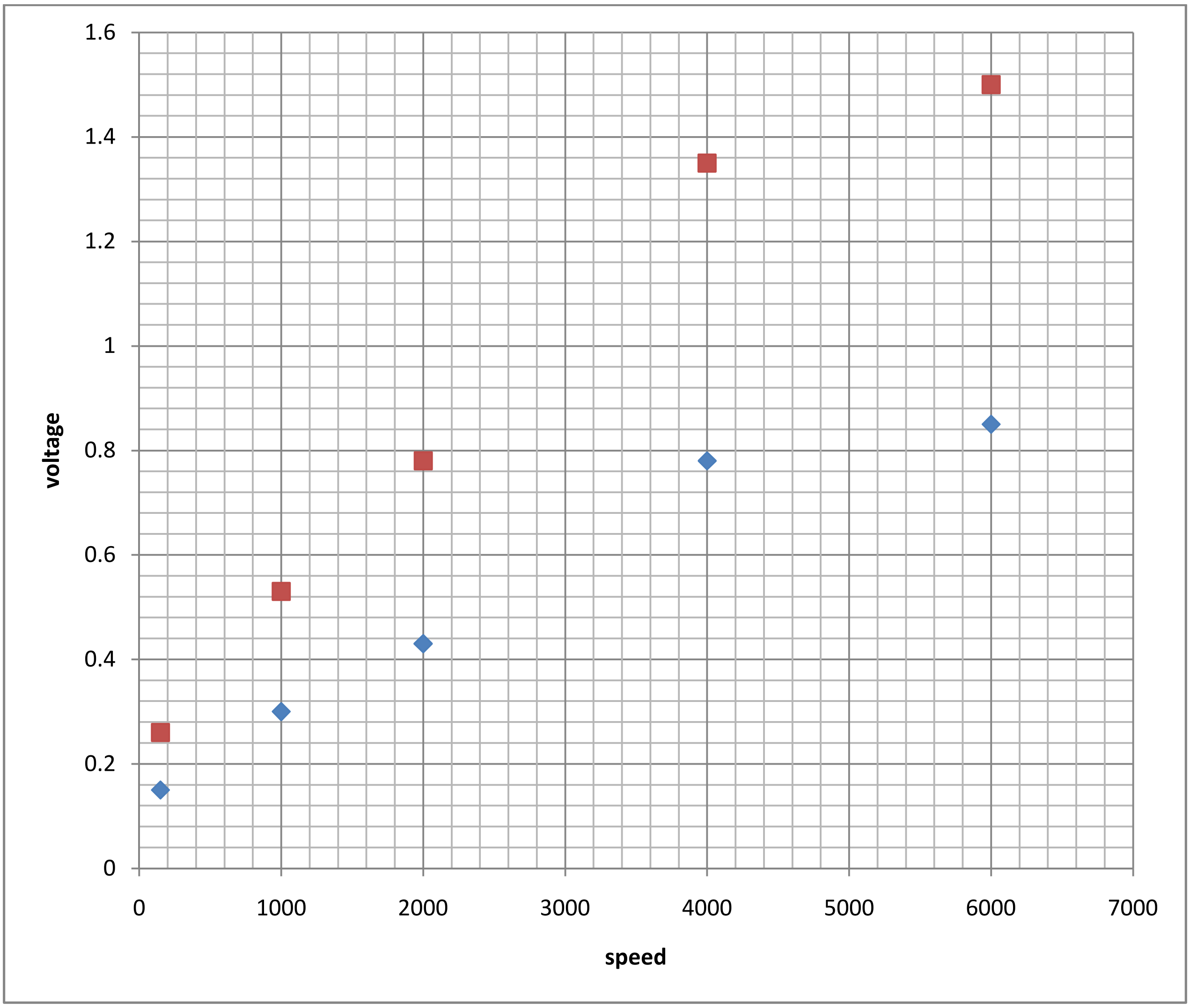
For 100 turns



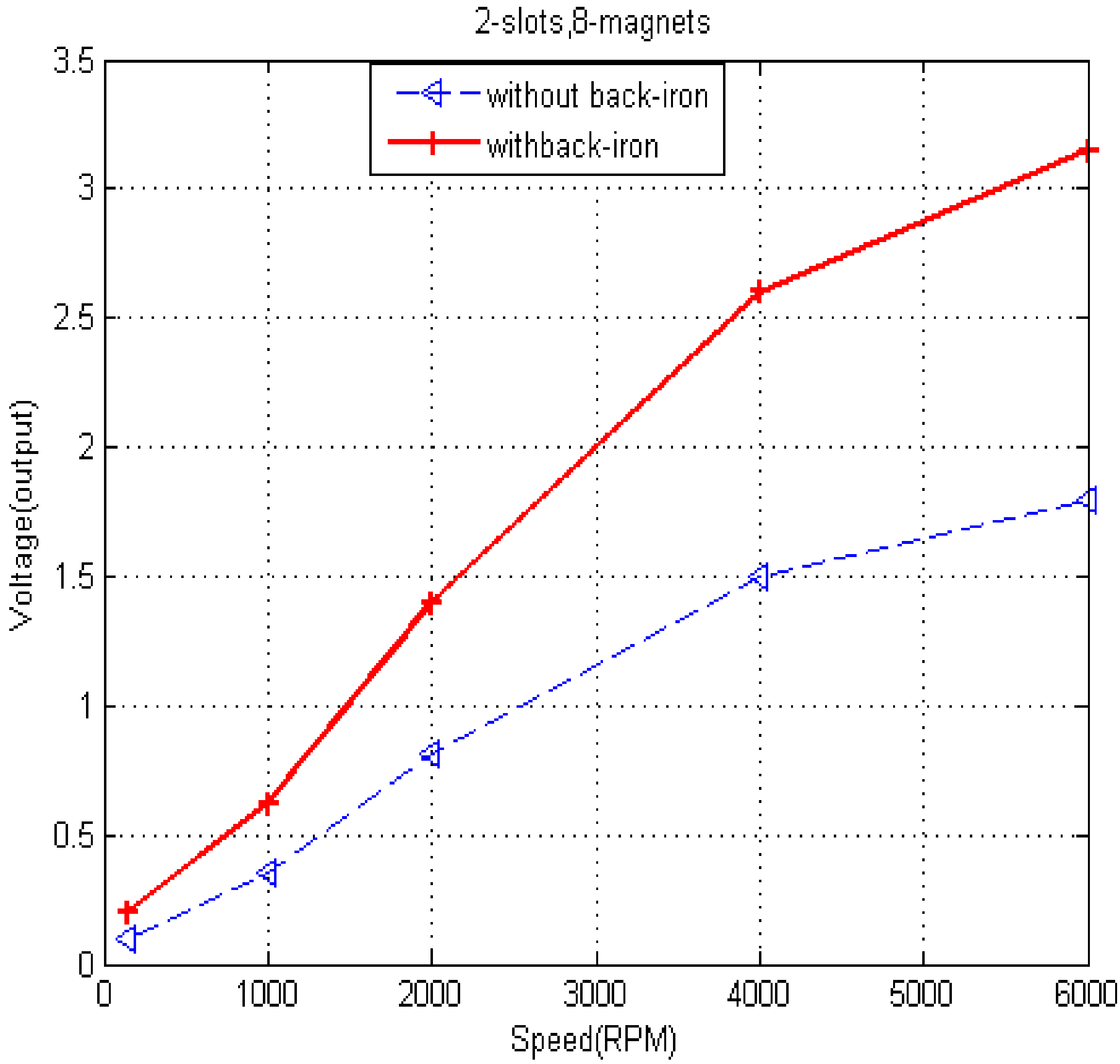
A10: For stator of 2-slots and a rotor of 4– magnets without back –iron inserted to the stator.



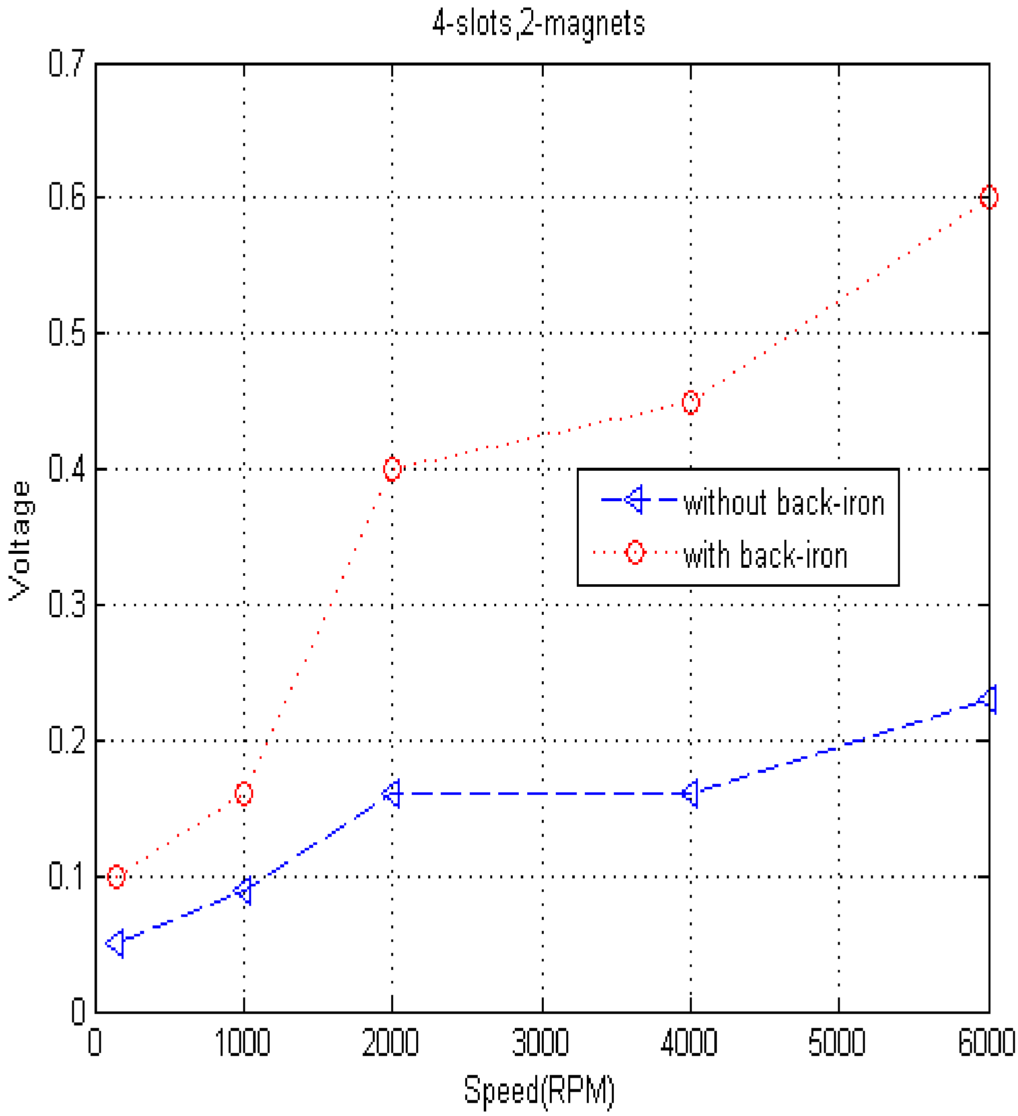
A11: For stator of 2-slots and a rotor of 6– magnets without back –iron inserted to the stator.



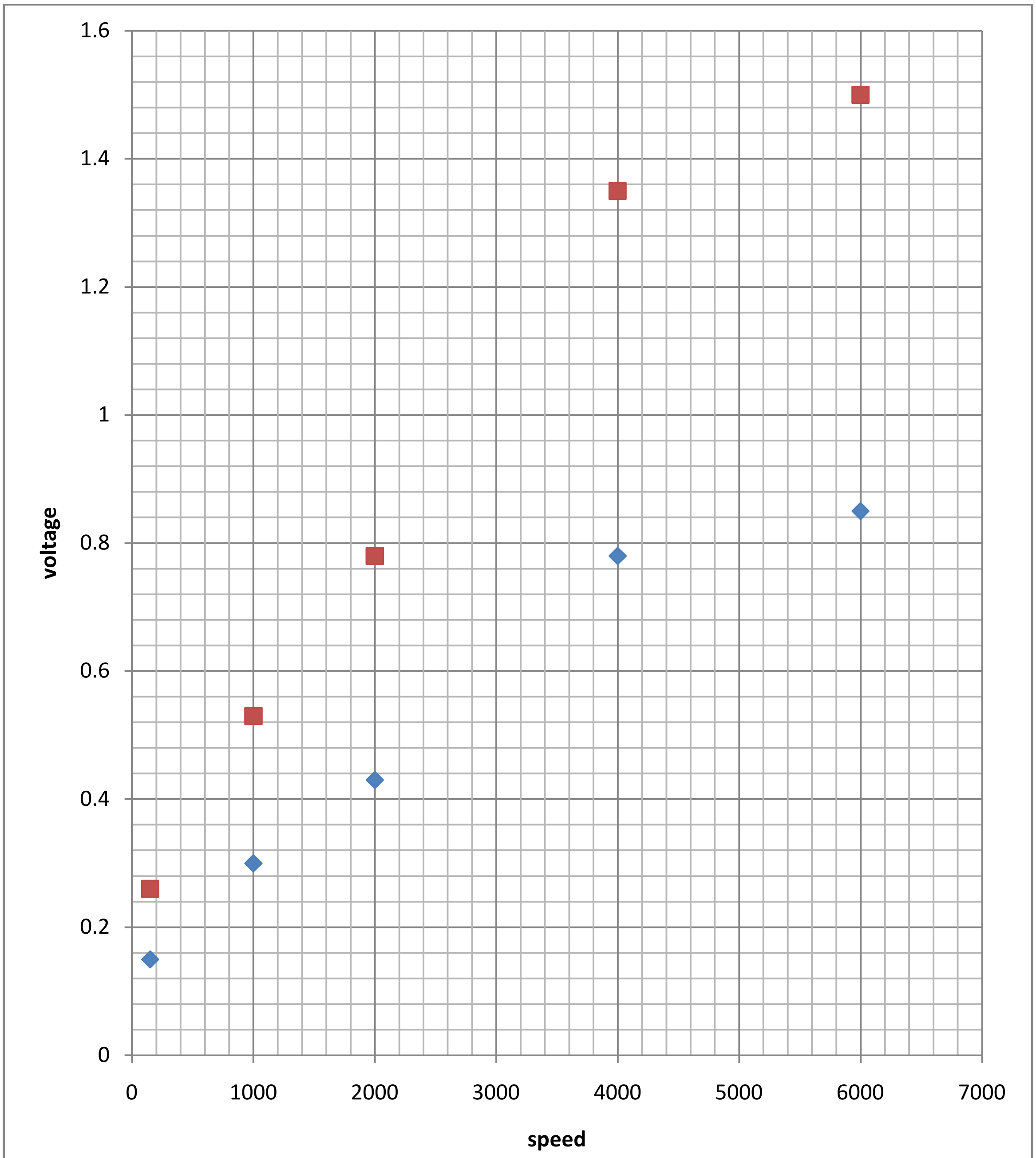
A12: For stator of 2-slots and a rotor of 8– magnets without back –iron inserted to the stator**.**



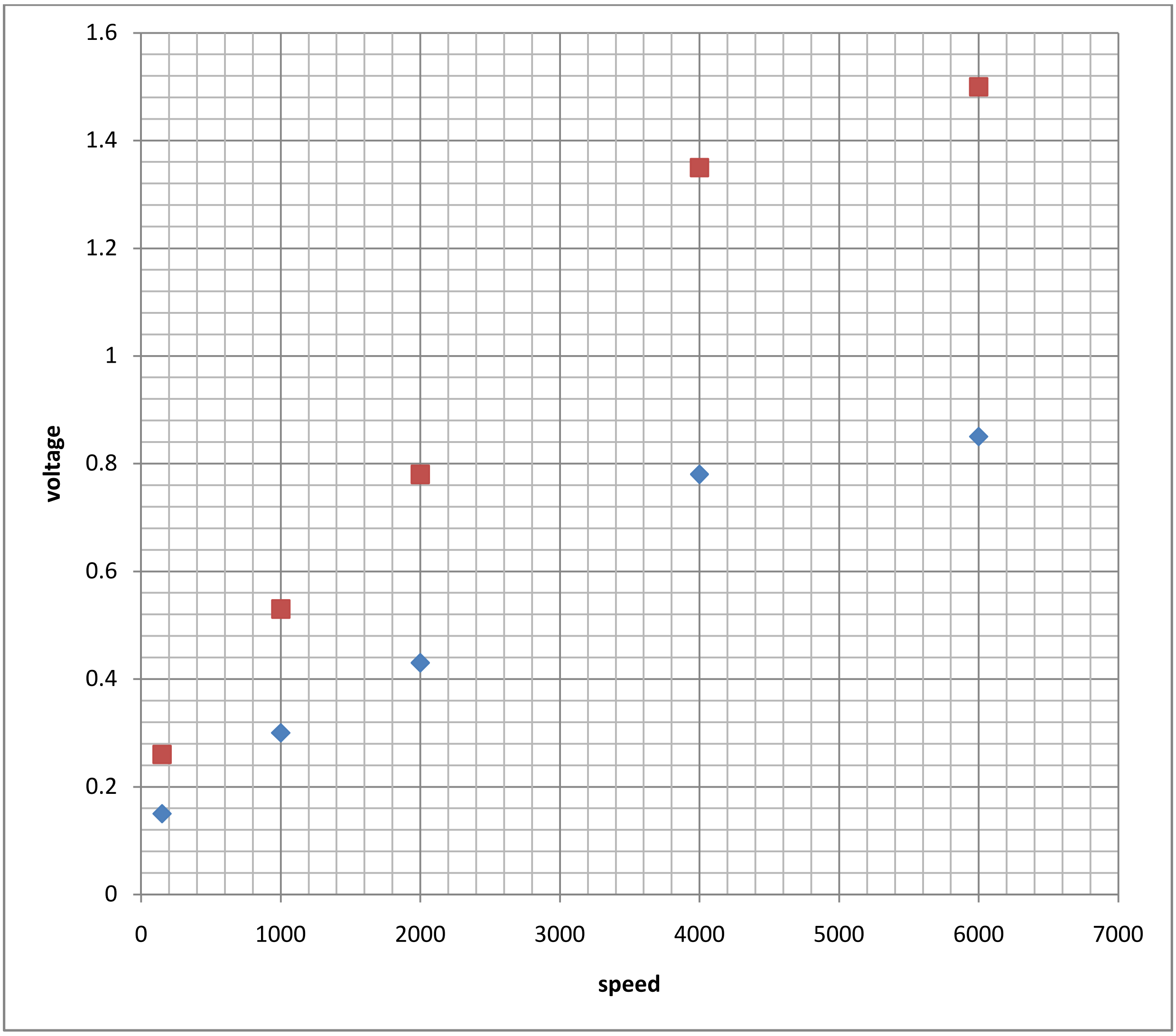
A13: For stator of 4-slots and a rotor of 2 – magnets without back –iron inserted



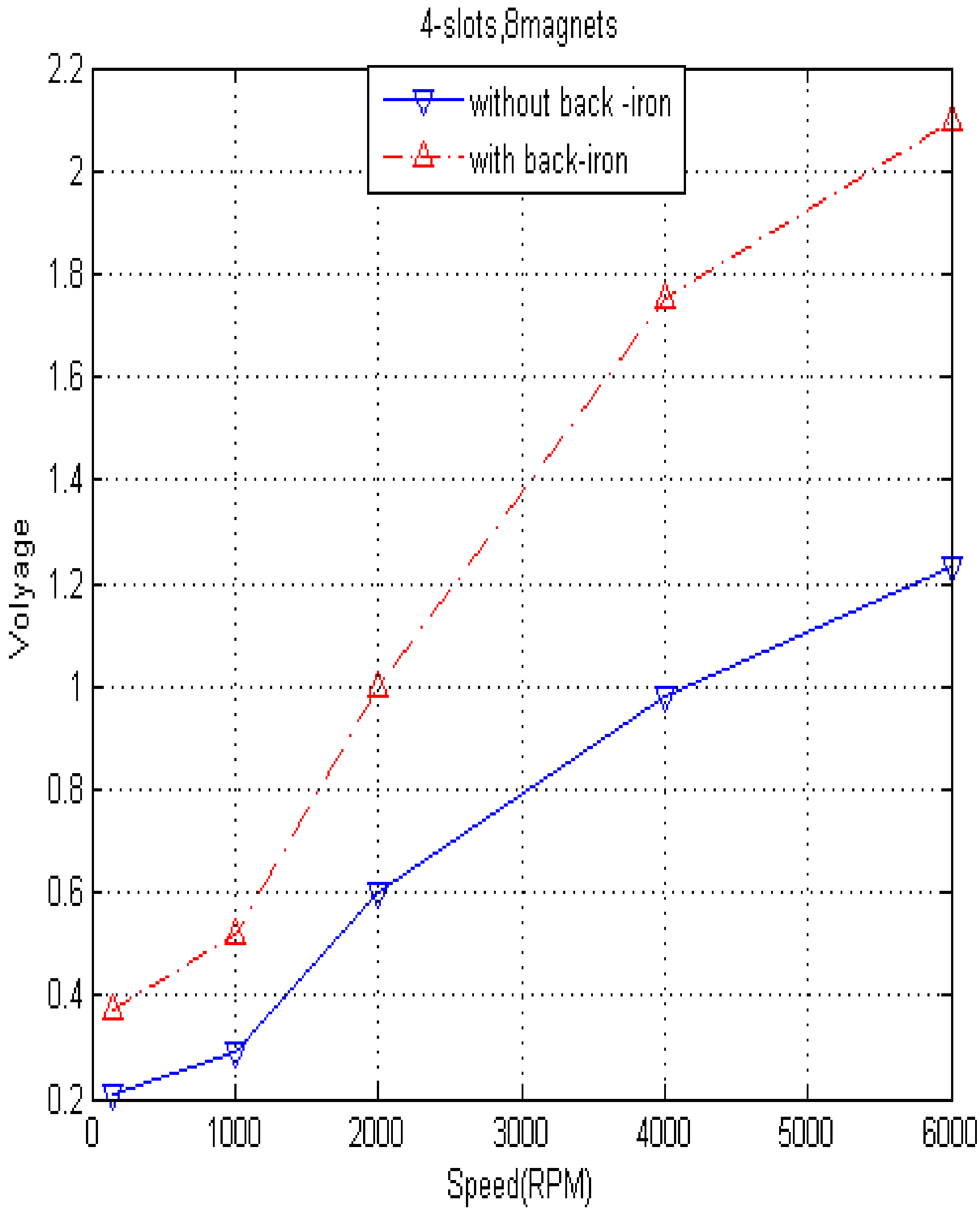
A14: For stator of 4-slots and a rotor of 4– magnets without back –iron inserted to the stator.



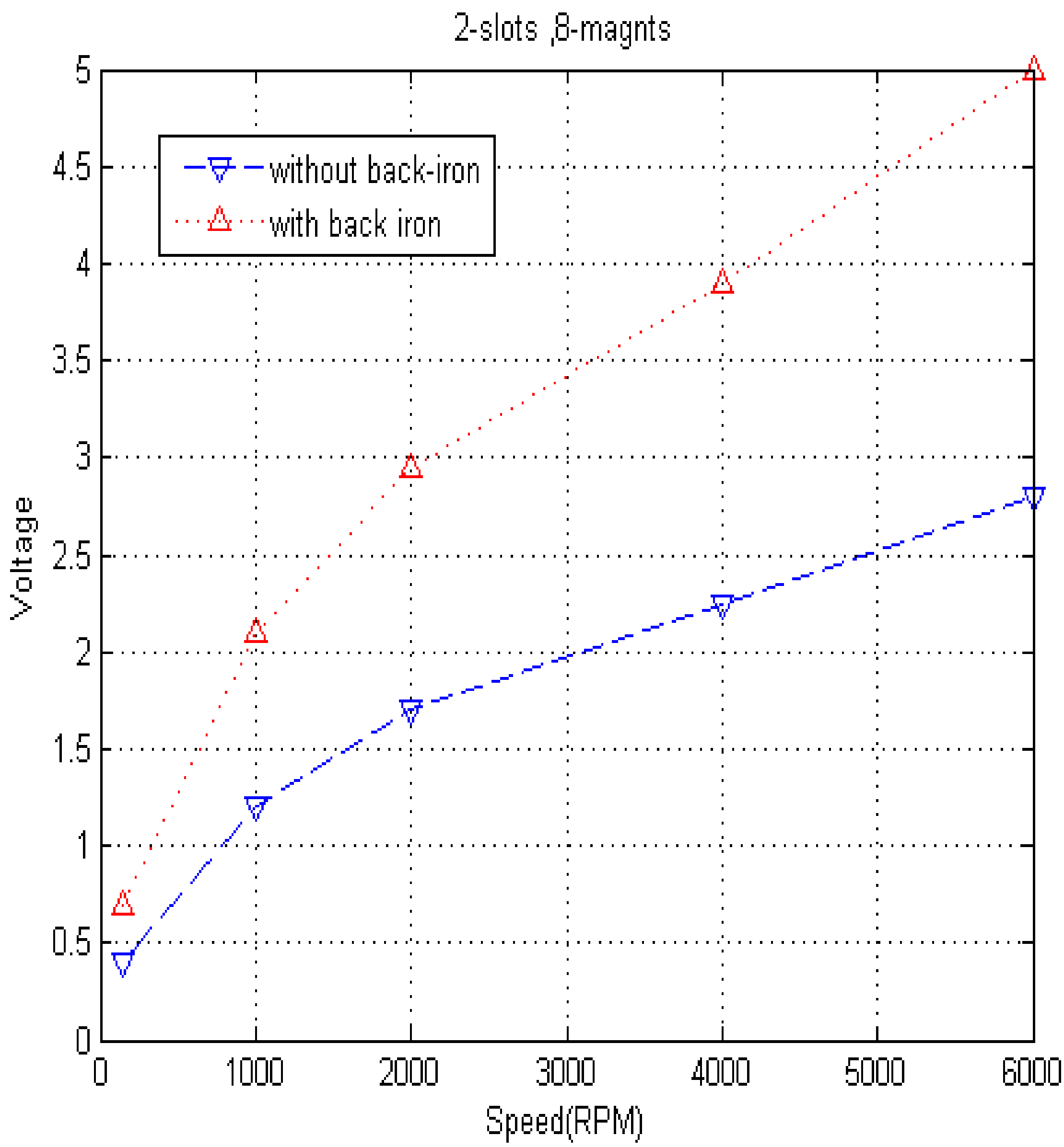
A15: For stator of 4-slots and a rotor of 6– magnets without back –iron inserted to the stator.



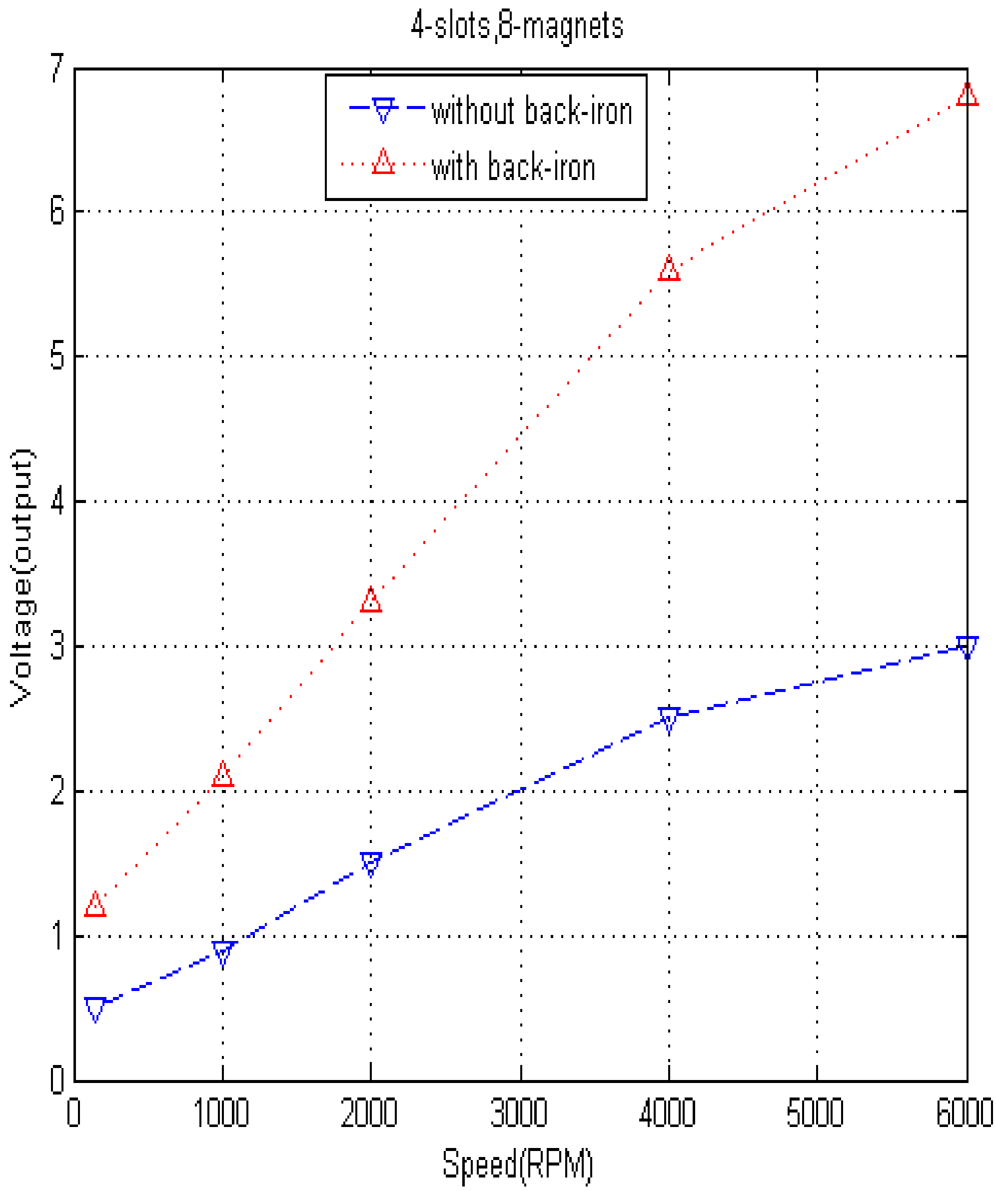
A16: For stator of 4-slots and a rotor of 8– magnets without back –iron inserted to the stator



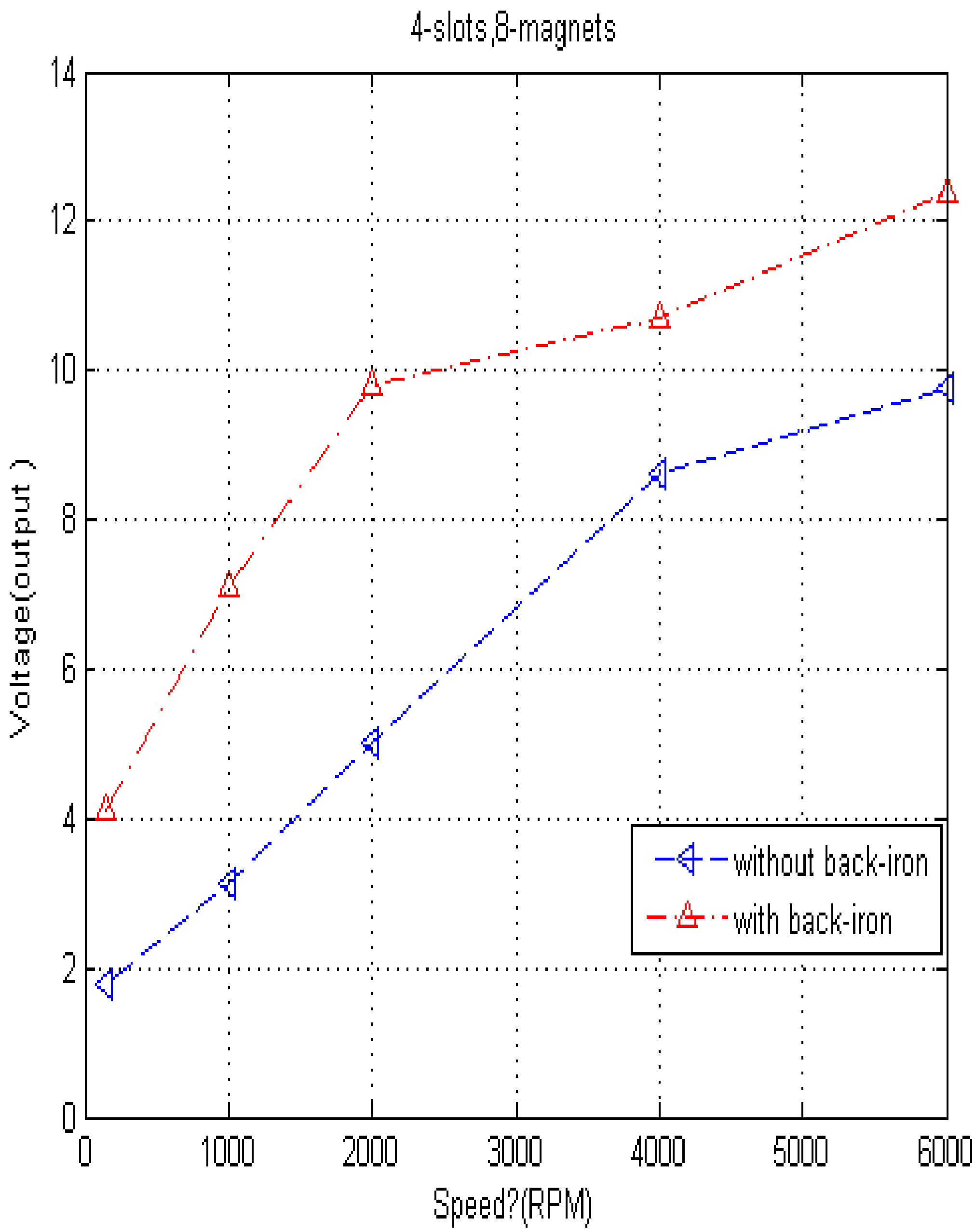
A17: For stator of 2-slots and a rotor of 8– magnets without back –iron inserted to the stator.



A18: For stator of 4-slots and a rotor of 8– magnets with back –iron inserted to the stator. For 300 turns



A19: For stator of 4-slots and a rotor of 8– magnets without back –iron inserted to the stator 500



" تصميم وتمثيل المولدات السائلة المصغرة لتوليد الطاقة الكهربائية "

اعداد

محمد عبد الرحمن علي أبورمان

المشرف

الدكتور مضر الزغول

المشرف المشارك

الدكتور علاء الدين الحلحولي

ملخــــــــــص

كثافة الطاقة المتوفرة من البطاريات اصبحت كفاءة الاستخدام لها محدودة في مجال الالكترونيات النقالة . كنتيجة لهذا هناك حاجة متزايدة لكثافة عالية من الطاقة المضغوطة , هذا العمل يقدم تصميم و صناعة و اختبار المولدات من حجم الملم الذي يستخدم المغناطيسات لانتاج الطاقة . عدة اختبارات تحقيقية اجريت على المولدات المصنعة لهذة الغاية وايجاد عدد اللفات المناسب و عدد المغناطيسات التي يجب استخدامها و تحديد السرعة التي يجب اجراء الاختبارات عليها و حجم الطاقة المتولدة من هذا النظام الذي يستطيع توليد طاقة بما يقارب من مل واط الى واط. القرص بقطر 20 ملم تم تشغيلة فوق عدد من اللفات مما يؤدي الى حدوث حث مغناطيسي في الملفات و توليد طاقة كهربائية حسب قانون (فاراداي) للحث . هذة الاختبارات عرضت امكانية تطبيق و تطوير هذا النظام حيث تم توليد 1.45 واط على سرعة 6000 دورة في الدقيقة